The use of (cyclopentadienone)iron tricarbonyl complexes and ruthenium complexes for hydrogen transfer reactions

By

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Contents

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Finally, many thanks go to my family and friends, who have supported me throughout this PhD.

Declaration

The work described in this thesis is solely the work of the author unless otherwise stated. This thesis is submitted to the University of Warwick in support of my application for the degree of Doctor of Philosophy. It has been composed by myself and has not been submitted in any previous application for any degree at any other academic institution. The studies contained in this thesis were carried out at the Department of Chemistry, University of Warwick between December 2013 and November 2017.

Some of this work has appeared in the following publication:

Brown, T.; Cumbes, M.; Clarkson, G.; Diorazio, L.; Wills, M. *J Org. Chem.* **2017**, *82*, 10489-10503.

Abstract

The synthesis of (cyclopentadienone)iron tricarbonyl complexes and the application of said complexes to the catalysis of 'hydrogen borrowing' reactions between amines and alcohols has been studied.

A family of analogous (cyclopentadienone)iron tricarbonyl complexes were synthesised and used in 'hydrogen borrowing' with aniline and analogous alcohol reagents comprising increasing carbon chain length, in an attempt to gain more understanding of the effect of altering the electron environment of the hydroxy group of the active iron catalysts generated from the synthesised (cyclopentadienone)iron tricarbonyl complexes.

Utilising an alternative set of reaction conditions, the scope of the 'hydrogen borrowing' methodology was extended to include amines derived from piperidine, benzylamine and other aliphatic amines. The incorporation of additional functionality (e.g. alkene or alkyne groups) into the product amines was also found to be an option of the new methodology.

The synthesis of novel asymmetric (cyclopentadienone)iron tricarbonyl complexes was also attempted and a novel application of Ru(II)/TsDPEN hydrogen transfer catalysts was also discovered.

Introduction

(1.1) The Use of Iron in Chemistry

The use of iron in chemical processes, from both an academic and industrial viewpoint,[1] has become more prevalent within the last decade due to metal complexes becoming essential resources in the synthetic activities of organic chemists. This has been caused by the increasingly demanding requirement for catalytic reactions that possess a clean and selective reaction pathway. The associated high speed and efficiency of such processes has also become a factor of understandably great interest, as this can allow a chemist to access reactions were not possible beforehand. However, [1] there are disadvantages associated with the use of such metal-based reagents, which include having to use 'precious' or heavy metals that possess inherent high price and toxicity issues which, when the reaction require application to a large-scale format. Thus, low metal catalyst loadings are used to counteract such issues.

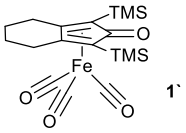
In contrast to the use of 'precious' metals (e.g. iridium, ruthenium, palladium or rhodium), the use of iron complexes involves significantly lower purchase costs, toxicity levels and the added advantage of significantly higher natural abundance. These reasons are why the use of iron has come to be recognised as a cost reducing and environmentally friendly catalytic alternative to the use of other metals such as platinum or palladium.

Despite the obvious advantages associated with use of iron, within the catalysis field, the use of iron-cased catalysts has not received a large amount of interest in research publications, in comparison to other more 'precious' transition metals. However, in the last decade, the use of iron-based catalysts in synthetic chemistry publications has increased significantly, to become an area of significant interest. This has been aided by the commercial availability of a number of iron reagents, several new applications of iron-based reagents have emerged, which have been shown to possess the ability to compete with 'precious' metals.

The types of iron reagents used in the catalysis of organic synthetic processes are highly diverse, but three significantly observed types of iron catalysts include; iron salts, iron pincer complexes and (cyclopentadieone)iron tricarbonyl complexes **1**. The third class being the main subject of this PhD project.

In terms of the other types of iron catalysts, iron salts and iron pincer complexes, the first mainly consisting of halogen-based iron compounds, such as, $FeCl_3$. Other compounds have been reported, such as, $Fe(ClO_4)_3$. The application of this type of catalyst has been reported to catalyse a large range of organic chemical reaction. Examples of this include addition reaction involving aldol, allylation and ring-opening reactions among others, substitution, cycloadditions, hydrogenation and polymerisation reactions.[1]

The second type of iron catalyst, iron pincer complexes **2**,[2] involve the use of a pincer ligand, which is a tridentate 6-electron donating ligand that coordinates onto the iron centre and provides a 'meridional' geometry onto the iron centre. While there is no strict rule as to what the pincer ligand may consist of, the general structure of this type of ligand often consist of a 1,3-disubstituted aromatic ring with the substituent groups comprising the chelating groups for the ligand. The produced iron pincer complexes have displayed high applicability to a number of areas of organic synthesis, through use in hydrogenation and polymerisation reactions, as well as, the functionalisation of alkene, alkyne and ketone-containing compounds.



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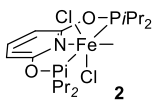
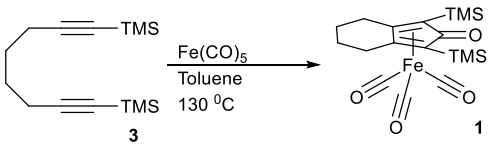


2

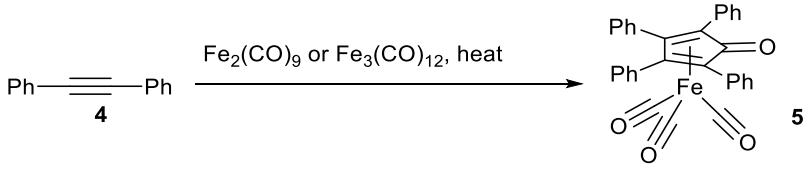
(1.2) Cyclopentadienone)iron tricarbonyl complexes

In general, the synthesis of (cyclopentadienone)iron tricarbonyl complexes **1** is carried out using an iron carbonyl source such as $Fe(CO)_5$, $Fe_2(CO)_9$ or $Fe_3(CO)_{12}$, which is used in a cyclisation reaction with an alkyne, a dialkyne **3** or the preformed cyclopentadienone, under conditions of high temperature and pressure (Scheme 1). This poses one of the main drawbacks of this chemistry, the toxicity of using iron carbonyl reagents at high temperature in a sealed reaction vessel generates a significant pressure of carbon monoxide gas. However, rigid health and safety procedures render the posed hazard to be minimal to myself and others around me.



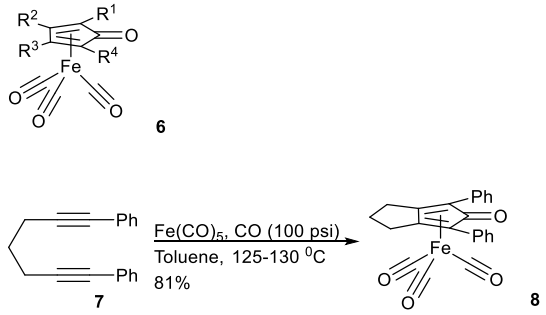
Scheme 1: Synthesis of (Cyclopentadienone)iron Tricarbonyl Complexes

The synthesis of (cyclopentadienone)iron tricarbonyl complexes has been known for just under 60 years,[3] but the synthesis of (tetraphenylcyclopentadienone)iron tricarbonyl complex **5** was reported by Shrauzer in 1959, using the reaction between either $Fe(CO)_5$, $Fe_2(CO)_9$ or $Fe_3(CO)_{12}$ and diphenylacetylene **4** as shown in Scheme 2. However this reaction was imperfect as this synthetic procedure produced a mixture of iron tricarbonyl-containing compounds. The paper also demonstrated the conversion via the generation of diiron- and triiron- complexes, which through the use of heat, can be decomposed to smaller iron-containing species.



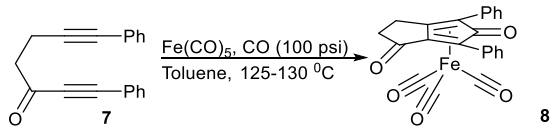
Scheme 2: Synthesis of Iron Complex 5

Published research interest into this type of iron complex did not appear again until the early 1990's, when the Pearson research group[4] first reported their synthesis of (cyclopentadienone)iron tricarbonyl complexes in 1992 with the synthesis of a range of structural derivatives of the Fe complex **6**. The R^1 and R^4 groups were either phenyl, Np-OMe, $SiMe_3$ or methyl groups and the R^3 and R^4 groups formed an alkyl chain of varying length or ketone functionality. This research group utilised the cyclisation of dialkynes, such as **7** with iron pentacarbonyl according to Scheme **2**, to give the iron complex **8**, using a high pressure vessel to carry out the reaction in order to contain the high pressures of carbon monoxide gas generated. The same synthetic procedure was then applied to a range of dialkynes to produce a series of complexes.



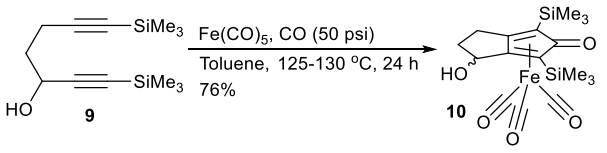
Scheme 3: Synthesis of Iron Complex 8

This research also explored the incorporation of a carbonyl group into the carbon chain linking the R^2 and R^3 positions. This type of transformation was then further investigated in a research paper published in 1994[5] which described the conversion of a range of iron complexes containing a carbonyl group (Scheme 4) into the corresponding chiral iron complexes containing an alcohol group.



Scheme 4: Synthesis of Carbonyl-containing Iron Complexes

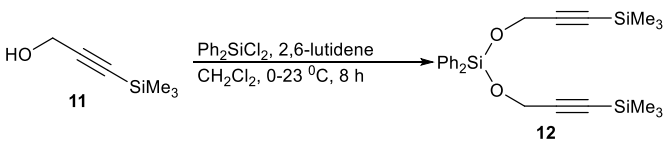
The synthesis of structural derivatives of the iron complexes was reported in a further paper in 1994,[5] which described the application of the earlier research to the preparation of chiral (racemic) Fe complexes **10** through the incorporation of an alcohol group into the starting racemic diyne **9**, as shown in Scheme 5.



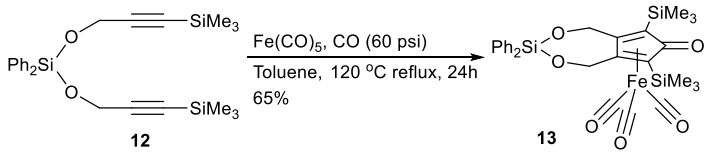
Scheme 5: Synthesis of Iron Complexes 10

Another application of the synthesis of this type of iron complex was described in a research paper published in 2002 by Pearson[6] et al., which concerns extended research into the synthesis of (cyclopentadienone)iron tricarbonyl complex derivatives as part of the synthetic procedure to produce cyclopentadienones through subsequent complex decomposition. This synthetic procedure involves the efficient combination of two 3-trimethyl-2-propyn-1-ol **11** molecules into a diyne derivative **12** containing a silyl ether moiety, (Scheme 6) and its subsequent cyclisation reaction (using $Fe(CO)_5$ and an atmosphere of CO) to give the iron complex **13** in a yield of 65% (Scheme 7). Further work was then conducted into other synthetic routes to cyclopentadienone complexes.

This research demonstrated that the synthesis of (cyclopentadienone)iron tricarbonyl complexes can also be used as a means efficiently synthesising cyclopentadienone derivatives (following decomplexation), which can be used in various additional applications. The chemistry of cyclopentadienones is a well documented area of chemistry and includes oxidation, reduction, Grignard additions and application to a Diels Alder-type reaction.[7]

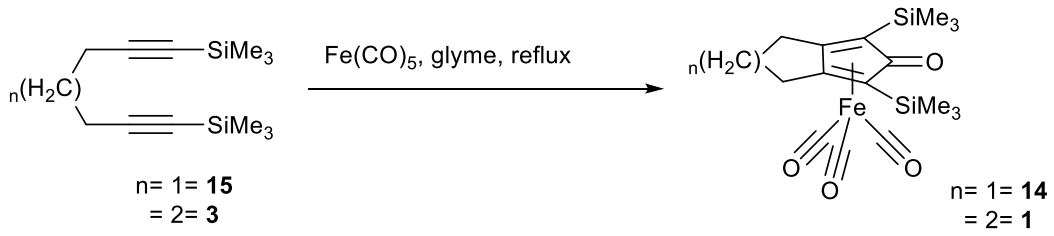


Scheme 6: Synthetic Route of Dialkyne Derivative 12



Scheme 7: Use of Dialkyne 12 For Synthesis of Iron Complex 13

In 1992, Knölker et al published a paper[8] describing the synthesis of cyclopentadienone iron tricarbonyl complexes **14** & **1** via the reaction of $Fe(CO)_5$ with the respective dialkynes **15** and **3** under reflux in glyme (Scheme 8). Iron complex **1**, where n=2, has come to be extensively utilised in publications detailing the application of (cyclopentadienone)iron tricarbonyl complexes for reduction and oxidation reaction.



Scheme 8: Original Methodology Used For Synthesis of Iron Complex 1

The synthesis of iron complex **1** marked a key point in this area of catalysis research, as this iron complexes comprises significant durability with regards to stability, as the complex can be synthesised in bulk and stored for many months. Minor alterations were made to the procedure displayed in Scheme 8 in subsequent publications concerning the application of (cyclopentadienone)iron tricarbonyl complexes to oxidation and reduction reactions. The majority of procedures still utilise $Fe(CO)_5$ as the source of the iron centre and all the carbonyl groups, but the choice of solvent may vary to the use of aromatic solvents, for example, toluene.

Although (cyclopentadienone)iron tricarbonyl complexes have been shown to possess lower toxicity levels in comparison to other transition metal-based catalysts, the use of iron carbonyl reagents, such as $Fe(CO)_5$, $Fe_2(CO)_9$ or $Fe_3(CO)_{12}$, poses considerable drawbacks in terms of health and safety considerations. The synthesis of the iron complexes generates high levels and pressures of carbon monoxide gas, which produces significant potential for severe health and safety hazards. However, the application of such iron complexes to oxidation and reactions has become the subject of considerable interest for research into iron catalysis.

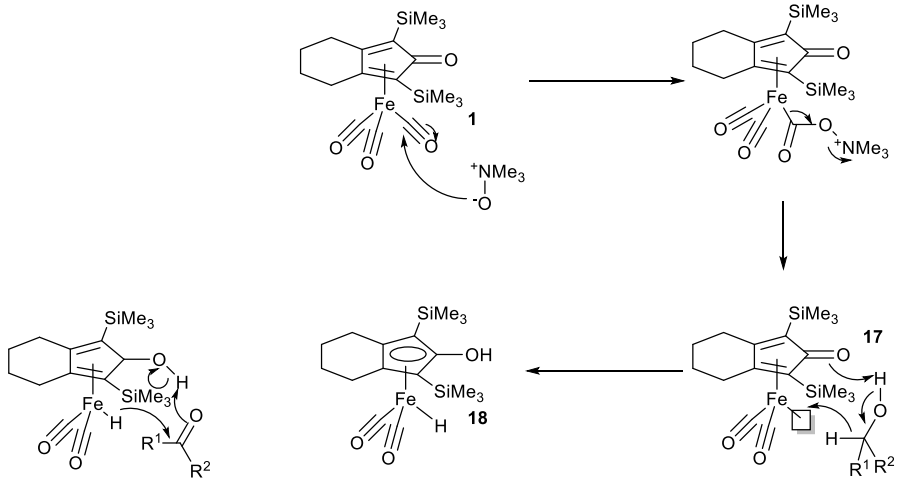
(1.3) Application of (Cyclopentadienone)iron Tricarbonyl Complexes to The Catalysis of Oxidation and Reduction Reactions

(Cyclopentadienone)iron tricarbonyl complexes have been observed to be highly applicable as hydrogen transfer catalysts for use in the oxidation of alcohol functional groups and the reduction of imine and carbonyl functional groups.

However, this type of iron catalysis did not become the focus of significant research interest for another decade after the publication of the series of research papers concerning the synthesis of (cyclopentadienone)iron tricarbonyl complexes in the 1990s, when the application of (cyclopentadienone)iron tricarbonyl to the oxidation and reduction reactions of alcohol and carbonyl functional groups became the subject of considerable interest in numerous research groups. The first case of this was in a publication by Casey et al.[9]

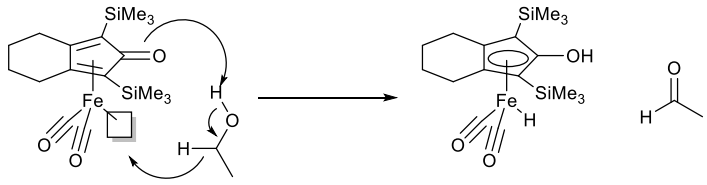
However, (cyclopentadienone)iron tricarbonyl complexes are inert and unreactive until they have been activated by removal of a unit of carbon monoxide. In the majority of all publications concerning the catalytic application of (cyclopentadienone)iron tricarbonyl complexes, the preferred method of catalyst activation is the use of an excess of trimethylamine *N*-oxide (typically 1-2 equivalents) with respect to the amount of iron complex being used (Scheme 9). This method of activation remove a carbonyl group and creates an empty valency

on the iron complex through loss of a unit of CO_2 and NMe_3. This provides a very effective and reliable means of iron catalyst activation.



Scheme 9: Use of Trimethylamine *N*-oxide For Iron Catalyst Activation

The empty valency on the iron complex provide the means by which the iron catalyst can gain two hydrogen atoms, e.g. from a primary or secondary alcohol, producing the iron-hydride form of the iron catalyst **18** and oxidising the alcohol-based compound to the corresponding aldehyde or ketone (Scheme 10).

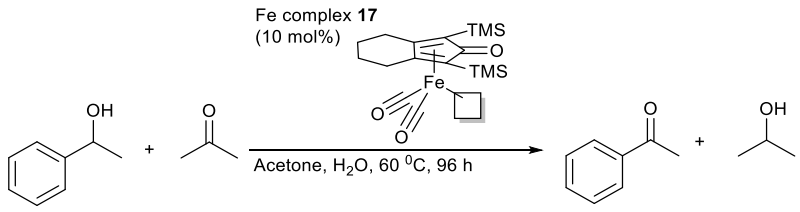


Scheme 10: Oxidation Mechanism

Before the activation of the iron complexes, the majority of known derivatives of (cyclopentadienone)iron tricarbonyl complexes exist as reasonably robust metal complexes that can be easily stored for extended periods of time without the need of inert storage conditions. However, after the removal of a carbon monoxide ligand from the iron complex, when the iron complex exists in either the unsaturated **17** or iron-hydride form **18**, the respective structures are significantly more unstable towards oxidising conditions (e.g. O_2 in air). Hence, all catalysed

reactions involving a (cyclopentadienone)iron tricarbonyl complex must be performed under inert atmosphere conditions (e.g. N_2 or Ar gas). A positive property of this type of catalysis is the observed tolerance of the activated iron catalyst towards any moisture found or produced by any catalysed reaction. An example of this concept is the generation of H_2O from the condensation reaction used in the imine formation reaction associated with the methodology of the 'hydrogen borrowing' reaction. The application of (cyclopentadienone)iron tricarbonyl complexes to 'hydrogen borrowing' reactions will be discussed in a subsequent section of this thesis.

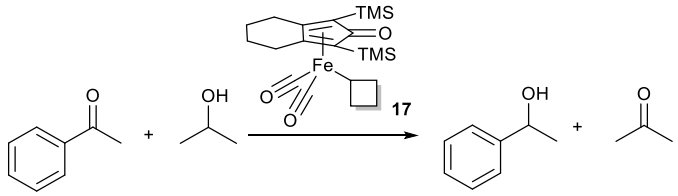
The basic principles behind the use of this type of oxidation or reduction reaction is to manipulate the equilibria of each reaction to drive the desired reaction to completion. In the case of the oxidation reaction (Scheme 11), the reaction is performed in a large excess of acetone as the reaction solvent, which serves as the hydrogen acceptor compound, thus generating isopropanol through the transfer of two hydrogen atoms from the hydride form of the iron complex to the acetone and regenerating the active iron catalyst **17**. It is the large excess of acetone that drives the reaction forward as the transfer of the hydrogen atoms from the iron complex to the hydrogen acceptor is made significantly more favourable, as the relative amount of isopropanol being produced is significantly smaller.



Scheme 11: Oxidation reaction

As can be deduced, the principles behind the use of this type of iron complex for a reduction reaction are essentially a reverse of the process utilised in an oxidation reaction (Scheme 12). In this case, a hydrogen donor is used with the activated iron complex to facilitate the reduction process.

The type of hydrogen donor being used can vary and includes the use of an alcohol (e.g. isopropanol), formic acid or pressurised hydrogen gas. In the case of formic acid, an additional factor drives the reaction in the desired direction; the generation of carbon dioxide gas, which is irreversibly released from the reaction environment. In all three types of hydrogen donor, the equilibrium of the reaction is manipulated to favour the reduction reaction pathway, either by utilising a large excess of the hydrogen source, such as pressurised hydrogen gas or a large amount of an alcohol (e.g. isopropanol) being used as the reaction solvent. The use of formic acid also provides a large excess of hydrogen with the above mentioned irreversible release of carbon dioxide gas as a by-product, thus shifting the equilibrium in a favourable direction.

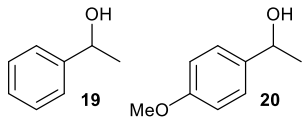


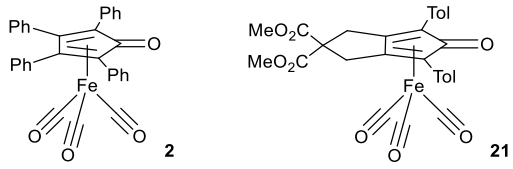
Scheme 12: Reduction reaction.

(1.4) Applications of (Cyclopentadienone)iron Tricarbonyl Complexes to The Oxidation of Alcohol Functional Groups

Thorson et al published a research paper[10] in 2009 concerning the oxidation of aryl alcohols **19** and **20** in order to examine the applicability of two different derivatives of (cyclopentadienone) iron tricarbonyl complexes **5** and **21**. The work in this publication was carried out in order to form a comparison of an established and published catalysis option with the use of iron complex **5**, against the use of a novel iron complex **25**. The overall results demonstrated that complex **5** displayed superior activity for the desired reaction over complex 5. The presence of the methoxide electron-donating group in the structure of alcohol **20** was found to be beneficial to the oxidation process and gave a yield of 79% and a conversion of 97% when complex **5** was used. However, it was found that when complex **5** was used

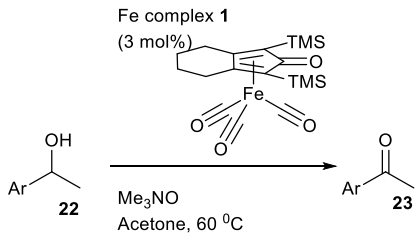
there was only a poor yield of 11% for the oxidation of 1-phenylethanol **19** and with the iron complex **5** there was an improved yield of only 38%.





The publication also described an investigation into addition of a reaction additive such as benzoquinone on the overall reactivity of the process and this was also found to not be beneficial for this type of oxidation reaction and it was found that the percentage yield of acetophenone from the oxidation of 1-phenylethanol through the use of complex **5** was decreased from 38 to 24%.

The iron complex **1** was utilised in a 2010 research paper[11] from Coleman et al, for the oxidation of a range of alcohols in excellent yields of 73 to 91%. As described in the preceding introduction to the principles of the oxidation process, the iron catalyst was employed as a hydrogen transfer catalyst for the conversion of the aryl alcohol-containing compound **22** to the corresponding ketone **23** and the reactions were found to be best carried out under the conditions illustrated in to Scheme 13.



Scheme 13: Application of the Oxidation Methodology

The oxidation reaction exploits the use of an excess amount of acetone as the reaction solvent and the hydrogen acceptor compound, thus providing an effective means by which to convert the hydride form of the iron catalyst **17** back to the original activated form in order to complete the catalytic cycle. Studies carried out in support of this published work suggested that the hydrogen transfer process takes place via the concerted process shown in Figure 1.

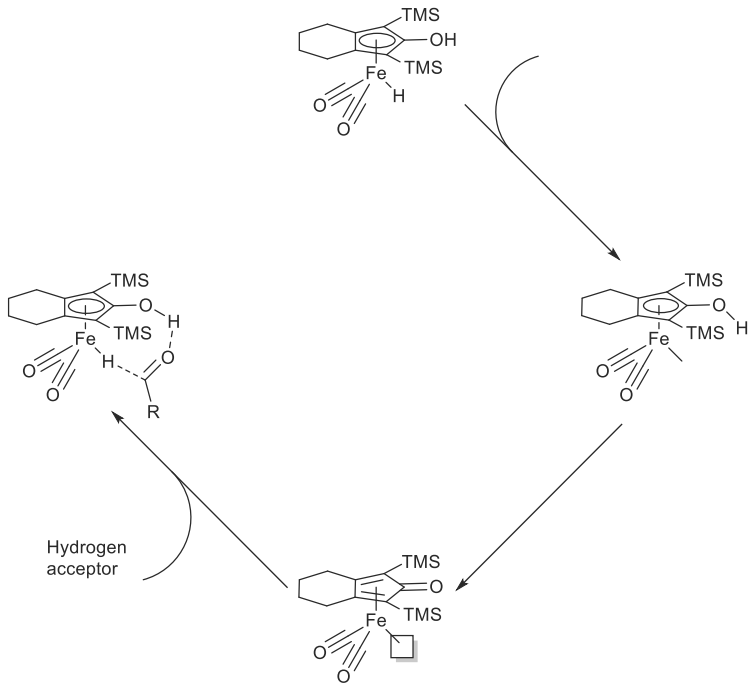
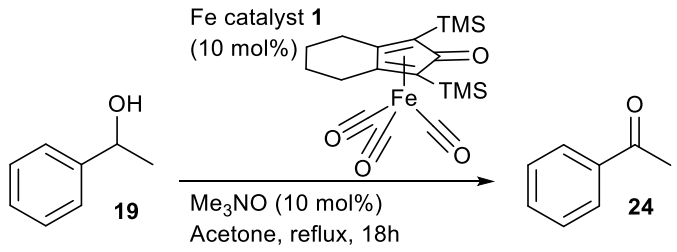


Figure 1: Reaction Pathway For The Oxidation Process

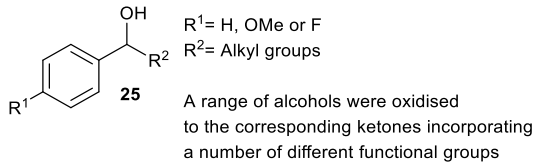
This research also demonstrated that this class of catalyst could be utilised to perform the oxidation of alcohols bearing a range of functional groups such as alkoxide, halogens, CF_3 or alkene groups without these additional functional groups causing any undesired difficulties under the utilised reaction conditions.

Another example of the use of the use of the iron complex **1** with acetone as an hydrogen acceptor and similar derivatives was published in 2010 by Funk et al,[12] who also utilised the catalyst as a means of carrying out the oxidation of alcohol compounds. In this case, trimethylamine N-oxide was again used as a means of performing an in situ activation of the catalyst by removing a CO ligand from the iron complex to create the active species **17** (Scheme 14).

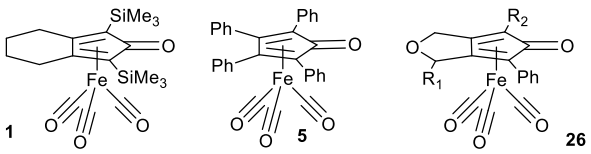


Scheme 14: Oxidation Reaction Methodology Used By Funk et al

The oxidation of 1-phenylethanol **19** to the corresponding ketone **24** was employed as a means of examining the applicability of this reaction and it was found that this reaction could be carried out in an excellent yield of 89% (Scheme 14). The scope of this method of oxidation was then investigated on a wide range of secondary alcohols **25** and it was found that the percentage yields varied widely from 40% to 94%.

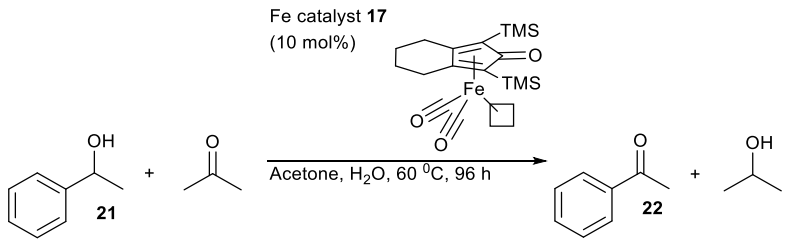


The use of (cyclopentadienone)iron tricarbonyl complexes as hydrogen transfer catalysts was the subject of a research paper published by Wills et al.[13] in 2010 where the oxidation of 1-phenylethanol to acetophenone was used to investigate the use of a range of (cyclopentadienone)iron tricarbonyl complexes **1**, **5** and **26**.



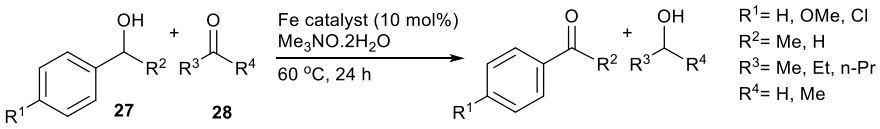
In a similar fashion to the previous example publications of the oxidation methodology, the synthesis of the iron complexes used demonstrated the relatively easy procurement of the iron complexes, as the iron complexes were all synthesised via a cyclisation reaction with the respective diynes and $Fe(CO)_5$.

This range of iron complexes were then examined for catalytic activity, at different catalyst loadings. The addition of water was studied, and the temperature and the time were also varied and it was found that iron complex **5** displayed much higher catalytic activity than the others; 95% of ketone was formed under the reaction conditions illustrated in Scheme 15 for the oxidation of 1-phenylethanol **21** to the corresponding ketone **22**. The other complexes under consideration gave very poor yields with only traces of acetophenone being obtained.



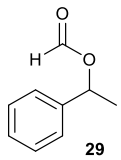
Scheme 15: Methodology Used By Wills et al

An attempt was then made in further work to improve the catalytic activity of the iron complexes by investigating the in-situ activation to the hydroxy cyclopentadienyl hydride iron complex with Me_3NO. Changing the hydrogen acceptor compound **28** and by altering the substrate **27** (Scheme **16**) was also investigated. Yields of up to 99% were obtained with the use of iron complex 2 and iron complexes **1** and **26** gave respective ketone conversions of up to 61% and 63%. The use of alcohol derivatives **27**, where R^1 refers to the use of para-methoxy groups, caused a significant acceleration of the oxidation process and gave yields of up to 100% within a much shorter time span of up to 6 hours. When R^1 refers to the use of a para-chloro group, the observed yield was reduced to 27-48%. The use of ketone and aldehyde derivatives **28**, saw no improvement to the observed yield through the use of alternatives to acetone.



Scheme 16: Investigative Work Into Choice of Oxidation Reagents

A novel application of this type of iron catalysis was then observed with the discovery of a novel synthetic procedure with the use of paraformaldehyde as a hydrogen acceptor. This also led to the formation of a quantity of a second product of the intended oxidation reaction, i.e. the formate derivative **29**.

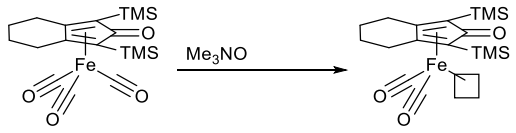


29

(1.5) Application of (Cyclopentadienone)iron Tricarbonyl Complexes to The Reduction of Carbonyl Functional Groups

The use of (cyclopentadienone)iron tricarbonyl complexes to catalyse the reduction of carbonyl functional groups through hydrogen transfer catalysis has become a well-documented area of published work. However, a great deal of the published work has been centred around the use of iron complex **1** as the hydrogen transfer catalyst. In part this popularity may be because the complex benefits from an efficient and cost effective synthetic access route, robust storage properties (i.e. can be stored for long periods of time without any significant degradation observed) and the complex appears to work effectively in both oxidation and reduction reactions.

Within the use of this type of catalysis, an established route for the activation of the iron complex to function as a hydrogen transfer catalyst was the use of trimethylamine N-oxide to serve as a means of removing a unit of carbon monoxide to leave an empty valency on the iron centre (Scheme 17), thus allowing the generation of the iron-hydride complex through the supply of a two hydrogen atoms from a hydrogen donor compound such as formic acid, or an alcohol.



Scheme 17: Activation of Iron Complex.

However, in recent publications carried out into reduction applications of the cyclopentadienone iron complexes, a new method of iron complex activation has been developed (Figure 2). Instead of utilising an *N*-oxide to carry out the activation step, a source of hydroxide ion is used to remove a unit of carbon monoxide from the iron complex. The source of hydroxide ion is achieved by carrying out the reduction reaction in an isopropanol/water solvent system and the use of potassium carbonate as an additive. The presence of potassium carbonate dissolved in water caused the creation of an equilibrium system to exist between

the water and the base, which causes potassium hydroxide to be present in a concentration high enough to achieve activation of the iron complex.

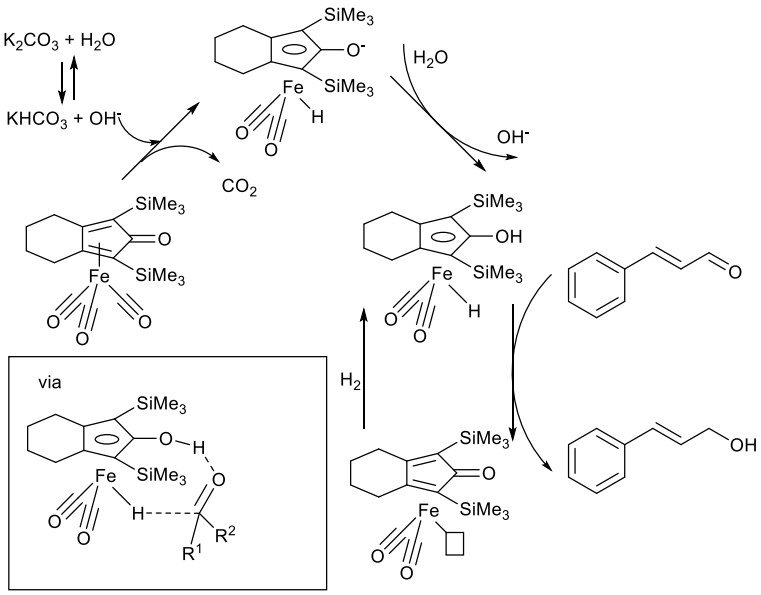
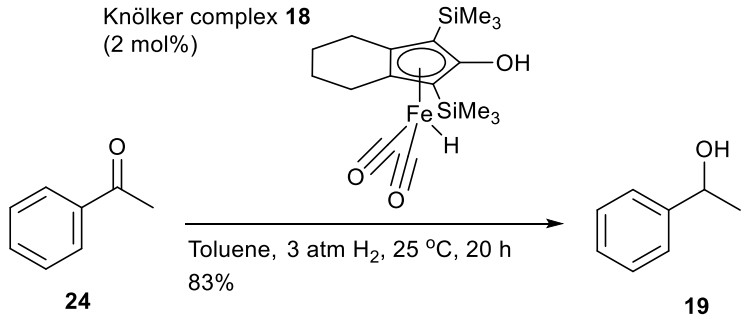


Figure 2: The Use of Hydroxide as an Iron Catalyst Activator Species

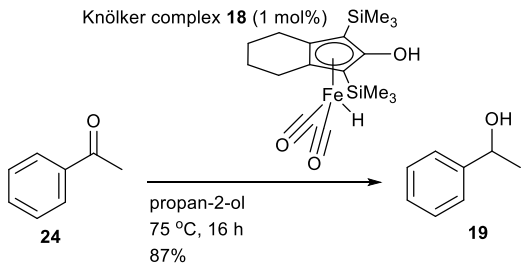
In an earliest example of the application of the (cyclopentadienone)iron tricarbonyl complexes to the reduction of carbonyl group containing compounds, a 2007 publication by Casey et al,[9] described the use of the activated iron complex **18** for the reduction of acetophenone **24** to the 1-phenylethanol **19**. This was achieved in an excellent yield of 83% (Scheme 18). This publication served as one of the main early building blocks of the understanding of the chemistry and methodology of the use of cyclopentadienone derived iron catalysts for reductive applications.



Scheme 18: Iron-catalysed Reduction Reaction

The scope of this type of use of the Knölker catalyst **18** was explored through the reduction of a range of aryl and unsaturated ketones and imines, which was successfully achieved with yields of 46% to 91%.

The application of the methodology to use with other hydrogen donor methods was also illustrated, with the reduction of acetophenone **24** being carried out through the use of transfer hydrogenation using isopropanol as the reducing agent. This work successful generated an alcohol in a yield of 87% (Scheme **19**).



Scheme 19: Use of Isopropanol As a Hydrogen Donor Compound

A subsequent publication by Casey et al[14] provided a detailed attempt to understand the more in-depth points of the catalytic mechanism for the reduction process and the reaction mechanism illustrated in Figure 3 was proposed. This depiction of the mechanistic route concurred with other published theories on the mechanism pathway of iron-catalysed reactions.

The studies revealed in this publication showed that the reduction reaction was a second order rate reaction, with first order for both the aldehyde and the iron-hydride species. Other results also revealed the highly labile nature of the alcohol-iron complex species observed, which further supports the proposed mechanism.

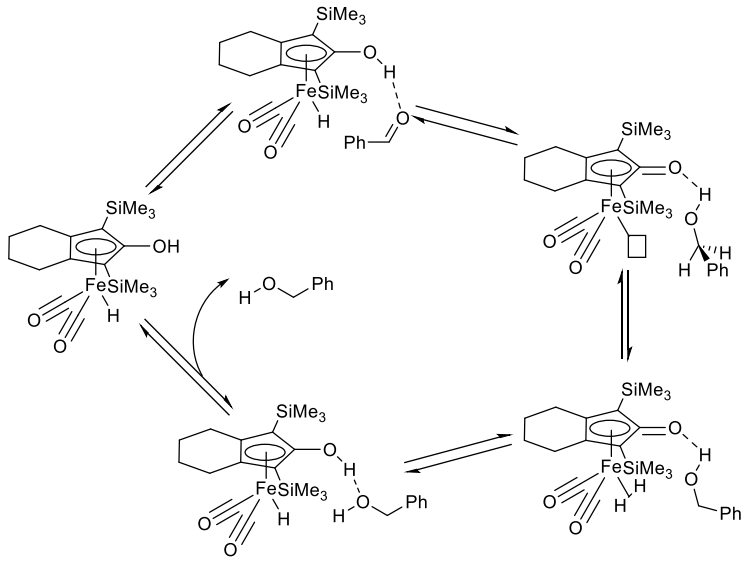
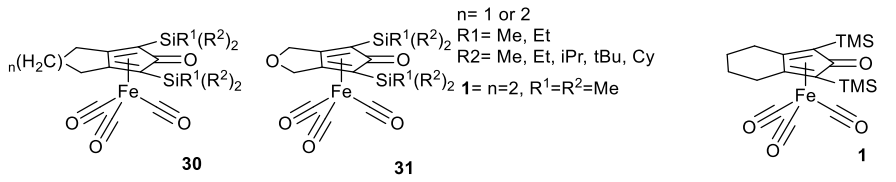


Figure 3: Mechanistic Study

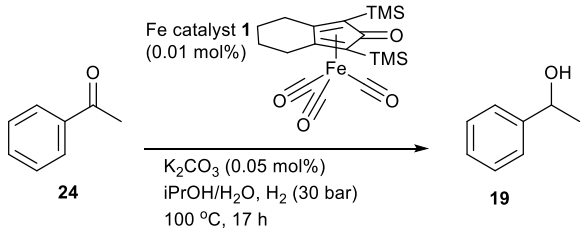
A mechanistic research paper was published in 2010 by the Zhang research group,[15] which detailed the mechanism as described in Figure 5 for the use of the hydroxy-hydride form of the Knölker catalyst for the hydrogen transfer to benzaldehyde. The presence of a hydrogen donor compound such as another alcohol-containing compound, regenerates the active catalyst (Figure 5). This study mirrors details revealed in the study carried out by Casey et al.[14]

A discussion was included of the use of dihydrogen as a means of activating the iron catalyst, instead of the use of a hydrogen donor compound (e.g. an alcohol-containing compound). This involves the coordination of H_2 onto the iron centre, producing a stable η^2-H_2 complex. Heterolytic cleavage of the H_2 then occurs between the Fe centre and the oxygen attached to the cyclopentadienone ring, which forms the desired iron-hydride species.

The development of this new method of iron complex activation was displayed in a publication from 2013, by Beller et al,[16] describing the reduction of ketones, aldehydes and α,β-unsaturated aldehydes. Catalysts **30** and **31** with either an ether or carbon chain moieties, were synthesised from the corresponding silated dialkynes through a cyclisation with iron pentacarbonyl, which has proven to be a common and effective synthetic route.

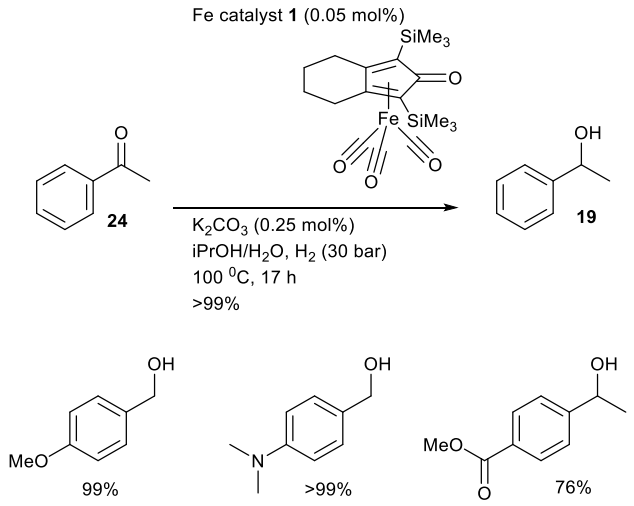


The reduction of acetophenone **24** to 1-phenylethanol **19** was used as a test reaction to examine the activity of the range of iron complexes to the reduction methodology and it was found that the iron complex **1** displayed superior catalytic activity for the reduction of acetophenone when activated with the alternate activation method, as illustrated in Scheme 20, using the K_2CO_3/H_2O methodology.



Scheme 20: Methodology Used By Beller et al

Following an in-depth study into the optimisation of the reaction conditions to be used with complex **1**, in terms of the catalyst loading, solvent, reaction temperature and the hydrogen gas pressure, it was found that catalyst loading could be decreased as illustrated in Scheme 21 to a level as low as 0.01 mol%, while maintaining a percentage yield of over 99%. This level of catalyst loading is significantly lower than levels utilised in other publications concerning the use of (cyclopentadienone)iron tricarbonyl complexes as oxidation or reduction catalysts. The standard catalyst loading used in other publications mostly varies between 3-10 mol%, demonstrating a significant advancement in the application of this type of catalysis to use as a hydrogen transfer catalyst for pressure hydrogenation reaction.

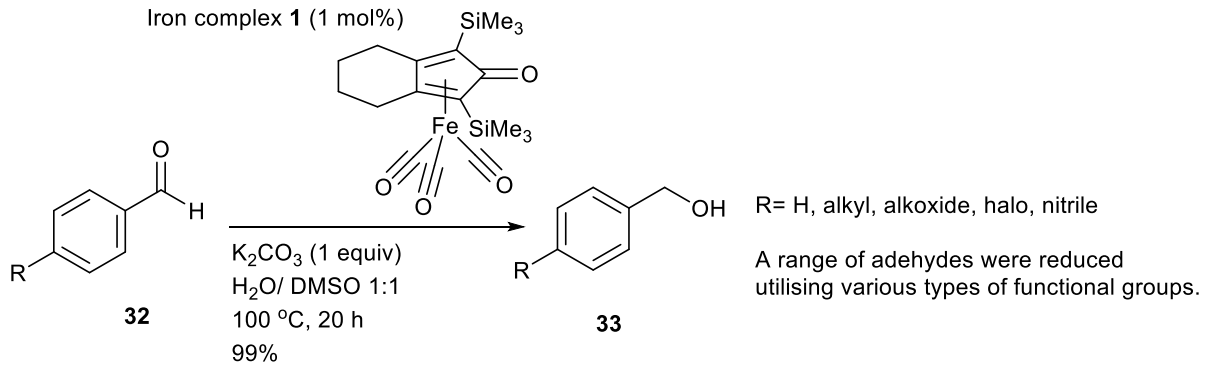


Scheme 21: Altered Methodology Used By Beller et al, Showing Product Examples

With these optimised reaction conditions in hand, the scope of this set of catalytic conditions was then explored by undertaking the reduction of a wide range of aryl ketones, which was achieved with excellent yields of mainly 76 to >99%. The use of this set of conditions was then extended to the reduction of alkyl ketones, aldehydes and α,β-unsaturated aldehydes in excellent yields of 82 to >99%.

The use of the Knölker catalyst was the subject of a research paper published in 2012 by the Beller research group,[17] again with a K_2CO_3 catalytic system and with water-gas shift conditions using CO and water present in the reactions as a source of the H_2 for the hydrogenation reactions.

The reduction of benzaldehyde **32** to benzyl alcohol **33** was used as a means of optimising the reaction conditions (Scheme 22). With this set of optimised conditions, the reduction was carried out with an excellent yield of 99% and this synthetic procedure was then applied to various aryl aldehydes and aldehydes with indole, furan or thiophene functional groups.



Scheme 22: Optimised Reaction Conditions Used By Beller et al

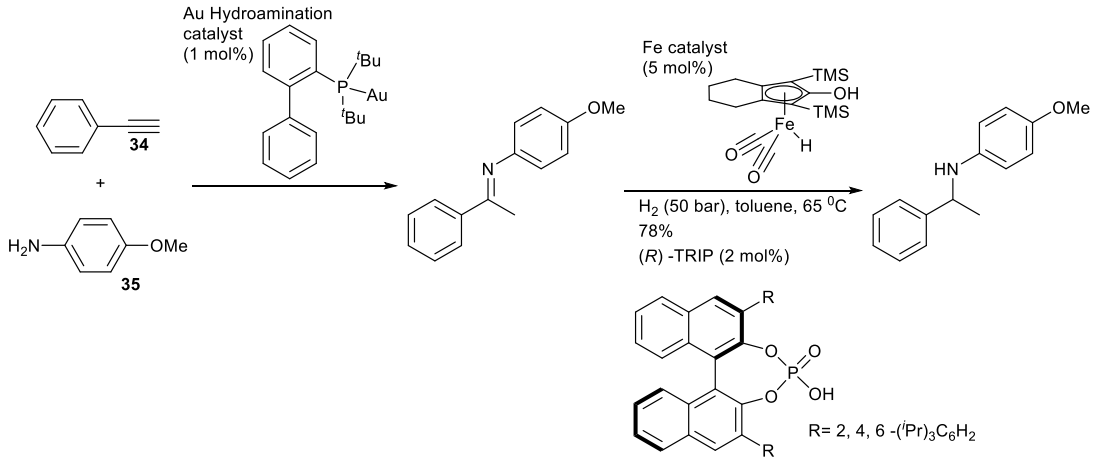
These reductions were carried out with excellent yields of 76 to 99%, except for the reduction of an aldehyde with a furan functional group (59%) and finally, the reduction of a range of α,β-unsaturated and aliphatic aldehydes were carried out with again excellent yields of 62 to 99%.

(1.6) The Application of (Cyclopentadienone)iron Tricarbonyl Complexes to The Reduction of C=N Functional Groups

A more recent published application of (cyclopenadienone)iron tricarbonyl complexes was as a means of reduction of imine functional groups to amine groups through a similar process as was used in earlier examples of carbonyl functional group reductions. As with the majority of other given examples of the application of this type of iron-based catalysis, the 'Knölker' catalyst **18** has formed the mainstay as the preferred choice of hydrogen transfer catalyst for the reduction of preformed C=N functional groups. This again has probably been largely the result of the proven applicability of this example of iron catalyst to both oxidation and reduction processes, as this saves considerable time and valuable research hours in developing new iron catalyst structures.

In 2012, the application of the Knölker iron complex **18** to the consecutive reduction of an imine C=N bond-containing compound to give amine **36** was described.[18] This reduction took place immediately after the coupling of alkyne group **34** to amine **35** using the Knölker catalyst as part of a catalytic system

involving the iron complex, a gold complex and a chiral Brønsted-Lowry acid (Scheme 23).



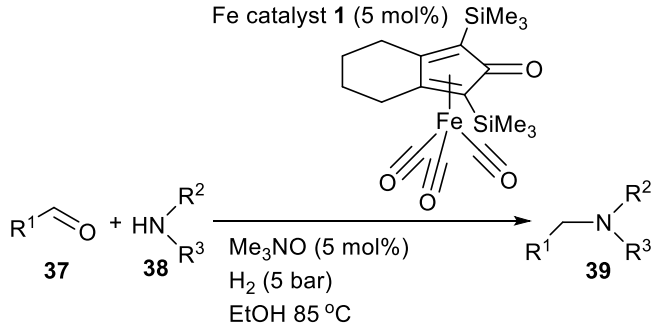
Scheme 23: Example of Amine Synthesis

The reduction step was then carried out separately and it was found that it could be carried out with a yield of 90% and an ee of 92%. The asymmetric aspect of the reduction being provided by the (*R*)-TRIP.

The use of biaryl phosphoric acid derivatives for the asymmetric reduction of imine-containing compounds, as shown by this publication, is based upon another earlier publication, which concerns a non-iron-based reducing system.[19] This example illustrated a route to amino esters through the reduction of the corresponding imines.

The use of the iron catalyst **1** was again the subject of a research paper published in 2012 by the group of Renauld et al,[20] which featured the application of the iron complex to the reduction of C=N functional groups in a range of imine derivatives that were generated in situ prior to the subsequent reduction and formation of secondary and tertiary amines. This work is also another example of the use of trimethylamine N-oxide as a means of activating the iron complex for the generation of the hydride-hydroxy form of the catalyst. The catalytic conditions are described in Scheme 24 for the reduction of a range of imines and enamines to the

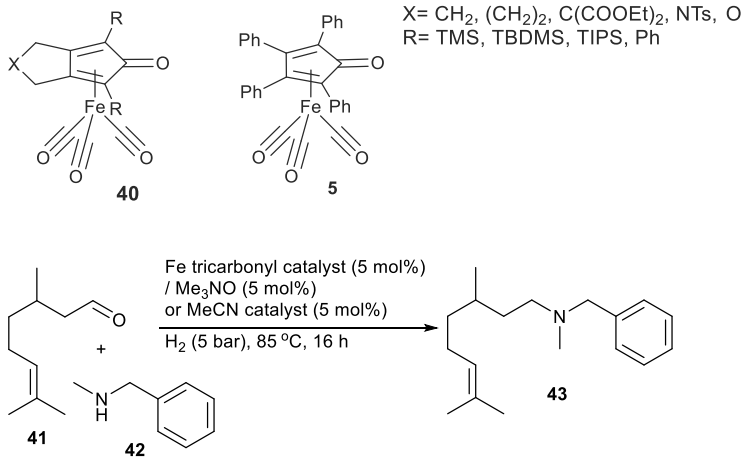
corresponding amines **39** after the coupling of a carbonyl group **37** to an amine group **38** with percentage yields ranging from 38% to 94% (Scheme 24).



Scheme 24: Methodology Used For Amine Synthesis

A change was then made to the reaction conditions detailed in Scheme 24, with the addition of NH_4PF_6, in an attempt to improve the selectivity of the reaction towards the amine product, but no improvement was observed.

A large range of iron complexes were synthesised in a subsequent research paper published by Renaud et al[21] included **5** and **40** and in each case, the published methodology involved the complexes undergo a CO ligand exchange for a MeCN ligand.

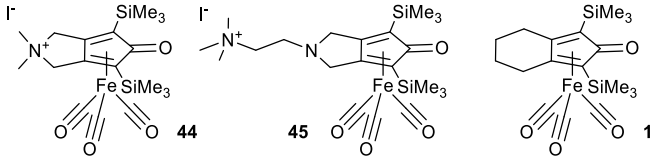


Scheme 25: Methodology Utilised By Renaud et al

A total of 11 iron complexes were then examined for catalytic activity in the reduction of an *in situ* formed iminium ion or enamine (Scheme 25). The initial coupling of a carbonyl containing compound **41** and an amine **42** was followed by reduction to give the tertiary amine **43** (Scheme 25). The catalyst derivatives generated a large range of yields from a poor value of 12% to an excellent value of 87%.

The scope of this synthetic procedure was then examined utilising the iron complex comprising an NTs and TIPS functional groups to catalyse a series of reactions involving N-methyl benzylamine and 2-phenyl ethylamine with a wide range of aliphatic and aryl ketones and aldehydes. The new synthesised catalyst displayed increased catalytic activity when compared to iron complex **1**, which was contrary to most other cases of iron catalyst development.

The reduction of C=O and C=N was the subject of a piece of research published in 2013[22] in which iron complexes **44**, **45** and 1 were examined for catalytic activity using the reduction of 4-methoxyacetophenone as a test reaction under various conditions involving variation to the iron catalyst and trimethylamine N-oxide loading, temperature and hydrogen pressure.

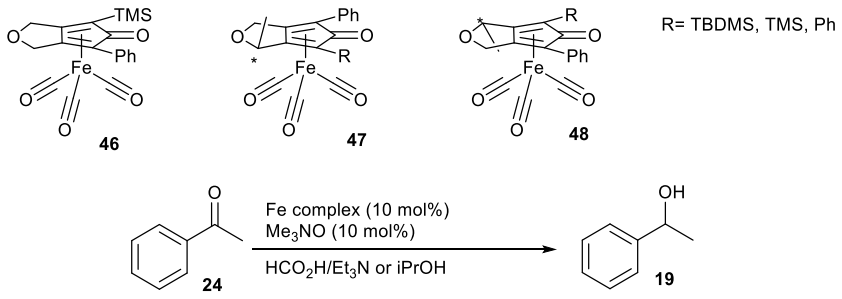


Iron complex **45-** displayed superior activity to the other two complexes for the reduction of a large range of aliphatic and aryl ketones and aldehydes, and cyclic imines, with yields ranging from a fair yield of 31% to an excellent yield of 98%.

(1.7) Application of (Cyclopentadienone)iron Tricarbonyl Complexes to Asymmetric Transfer Hydrogenation Reactions

Over the previous decade, there have been publications describing the development of asymmetric derivatives of (cyclopentadienone)iron tricarbonyl complexes for the asymmetric reduction of imine and carbonyl functional groups. The asymmetric characteristic can be introduced into the iron complexes through various methods, either through the exchange of a carbon monoxide ligand for a chiral ligand (e.g. phosphoramide ligand),[23] through the incorporation of chiral centres into the cyclopentadienone ring.[24]

The development of potential asymmetric examples of (cyclopentadienone)iron tricarbonyl complexes was the subject of publications in 2012 and 2016 from Wills et al.[24] The earlier publication featured the synthesis of iron complex derivatives **46**-**48** and the reduction of acetophenone **24** to 1-phenylethanol **19** (Scheme 26) was used to examine each iron catalyst for asymmetric activity.

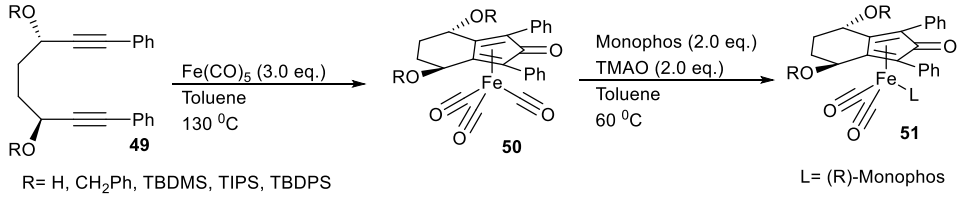


Scheme 26: Attempted Application to Asymmetric Reduction Reactions

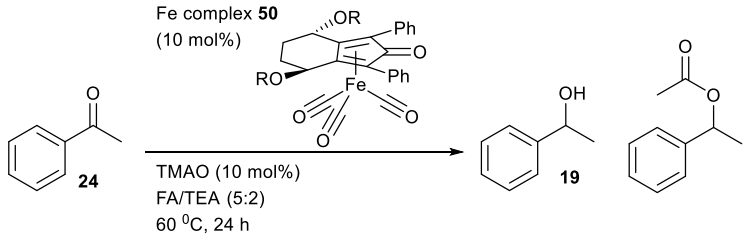
Iron complex **46** is an example of a series of complexes that possess the ability to catalyse an asymmetric reduction reactionand werewere tested to show that the asymmetric potential was a function of the functional group pairings (e.g. a smaller TMS group vs. a larger phenyl ring) that are differently sized. The incorporation of an asymmetric character into the synthesised iron complexes that possessed the structure represented by **47**-**48** was also attempted through the use of chiral centres (*) within the cyclopentadienone ring. The incorporation of these chiral centres cause the iron complexes to exist as a pair of enantiomerically-pure

diastereomers which were separated and each then in turn tested in the reduction of acetophenone (Scheme 25), giving conversions of up to 91% and ee values of up to 25% (R configuration).

In a more recent publication from Wills et al,[25] the use of chiral centres in the cyclopentadienone ring were used to synthesise a series of asymmetric (cyclopentadienone)iron tricarbonyl complexes **50** that were derived from C_2-symmetric diols **49** (Scheme 27). The use of chiral ligands to generate iron complexes **51** was also used as a means of increasing the obtained ee values of alcohols obtained from the catalysed reduction or oxidation reactions.



Scheme 27: Synthesis of Novel Asymmetric Iron Complexes



Scheme 28: Asymmetric Reduction of Acetophenone.

R group	Alcohol Conversion / %	Alcohol ee / %
H	83	14
CH_2Ph	65	22
TBDMS	86	12
TIPS	76	23
TBDPS	79	12

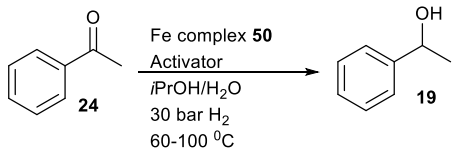
Table 1: Example e.e. Values With Use of Iron Complexes shown in Scheme 24

The synthesised iron complexes **50** were tested for the asymmetric activity through use as the hydrogen transfer catalyst for the reaction of acetophenone **24** with formic acid being used as the hydrogen donor compound and trimethylamine *N*-oxide as the catalyst activator (Scheme 28). These reaction tests showed that the novel iron complexes **50** gave alcohol conversion of up to 86% (Table 1), rivalling the conversion obtained with the use of the non-chiral 'Knölker' catalyst **18**, and a conversion to the formylated product of up to 54%. However, this high conversion to the formylated product was associated with the use of a lower catalyst loading of the iron catalyst and higher loading of the iron catalyst (e.g. 10 mol%) gave lower conversions of up to 23%. The use of lower catalyst loadings is a desired and more cost-effective route to take, as the use of higher catalyst loadings has anegative impact with the use of iron complexes, as even though the use of iron possesses a considerably lower cost, the majority of the cost involves the synthesis of the ligands.

The enantiomeric excess value's obtained from these tests showed no improvement upon the values obtained in the previous publication, with alcohol ee values of up to 24% obtained. The use of iron complexes **51**, which had undergone the exchange of a carbon monoxide ligand for a (*R*)-MONOPHOS ligand, revealed no increase in the obtained ee values and lower conversions of *ca* 7%. These results complimented the results published by Funk,[12] who had previously reported a

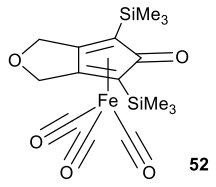
similar effect of introducing a phosphine ligand onto a (cyclopentadienone)iron tricarbonyl complex.

The developed iron complexes **50** were then applied to the catalysis of the pressure hydrogenation of acetophenone **24**, which also assessed the catalyst activation method, comparing the use of TMAO and K_2CO_3/ H_2O (Scheme 29). The results of this investigation showed the use of TMAO and a temperature gave the highest conversion values of up to 100% and ee values of up to 13% were obtained with respect to the R configuration.



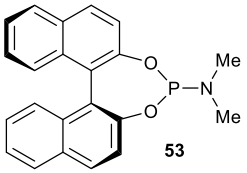
Scheme 29: Pressure Hydrogenation of Acetophenone

Another example of a publication displaying the attempted development of an asymmetric form of the (cyclopentadienone)iron complex was a publication by Berkessel et al,[23] featuring the attempted use of UV irradiation to synthesise chiral iron complex derivatives from iron complex **52** and use in hydrogenation reactions.



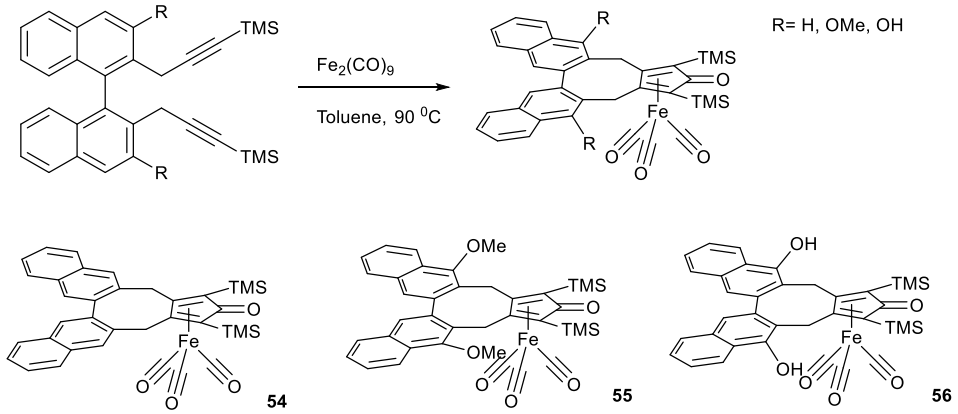
52

UV radiation was used to photolytically remove a CO ligand and allow the insertion of a chiral phosphoramidite ligand **53** to produce a chiral complex with poor yield of only 20%. The research group then worked on the synthesis of the same chiral complex through the use of TMANO to remove a CO ligand and allow insertion of the same chiral phosphoramidite ligand **53** with an improved yield of 94% for the *R* configuration ligand. This application of UV radiation was used in a subsequent publication by Wills et al.[24]



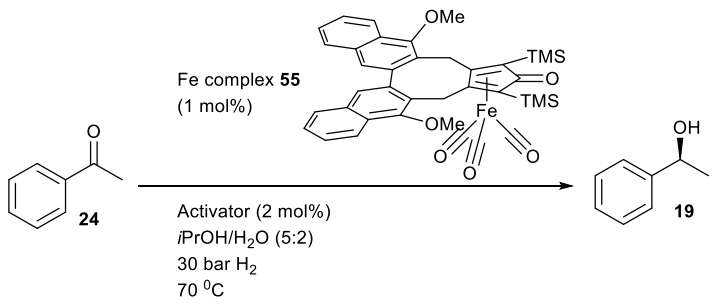
53

In a more recent publication by Gennari et al,[26] a novel approach was attempted to synthesise novel examples of asymmetric (cyclopentadienone)iron tricarbonyl complexes by synthesising this type of iron complex from a BINOL- derived dialkyne precursor compounds (Scheme 30), synthesising iron complexes **54**-**56**.



Scheme 30: Synthesis of Novel Iron Complexes.

These three iron complexes were applied to the asymmetric transfer hydrogenation of acetophenone **24** under pressure hydrogenation conditions (Scheme 31) and an assessment of different potential iron catalyst activators (e.g. TMAO, K_2CO_3, LiOH, NaOH) was made. To date, the results for iron complexes **55** and **56** provided the highest reported ee values for the asymmetric reduction of acetophenone through the use of a (cyclopentadienone)iron derived iron catalyst, with ee values of up to 47-53%.



Scheme 31: Asymmetric Reduction of Acetophenone.

The publication reported further explorative work regarding optimising solvent and temperature conditions for the reaction and while changes to the solvent conditions gave no significant effect upon the reaction outcome, a decrease in reaction temperature to 50^0C gave a slightly higher ee value of 55%, but again, this is no significant increase in the ee value.

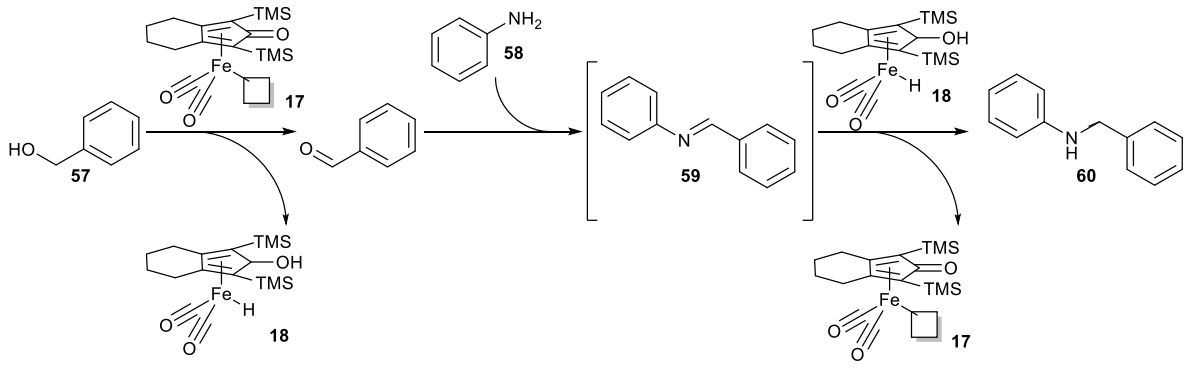
The reduction of prochiral ketones using asymmetric transfer hydrogenation (ATH) can also be achieved using other types of iron catalysis, for example, iron catalysts derived from PNNP ligands.[27] A publication from 2015[27] illustrated the use of Fe, Ru, Co and Ni complexes derived from PNNP ligands, for the reduction of prochiral ketones, with the iron-based examples producing e.e. values of up to 98%, which is siginicantly higher than what can be currently achieved using iron complexes derived from cyclopentadienone ligands.

(1.8) 'Hydrogen Borrowing'- The Alkylation of Amines

'Hydrogen borrowing' or hydrogen autotransfer[28] has become the focus of significant research interest due to the ability of the methodology to exploit the generation of carbonyl functional groups, which possess a wider range of potential reaction pathways, including imine formation, which allows convenient access to amine-containing compounds. The catalytic synthesis of amines through 'hydrogen borrowing' has fuelled the associated research interest as amine functional groups are found in a significant number of natural products and pharmaceuticals. The

ability to provide a catalytic pathway for the synthesis of such compounds has become an area of significant interest.

The term 'hydrogen borrowing' has been adopted to refer to the organometallic catalysed reaction to generate a C-N or C-C bond with the release of H_2O and the regeneration of the active catalytic species. The process involves the use of a primary or secondary alcohol with a primary secondary amine (Scheme 32). Although the use of the 'hydrogen borrowing' methodology with other organometallic complexes, such as those comprising of ruthenium, iridium or rhodium has been well documented, the use of (cyclopentadienone)iron tricarbonyl complexes as a more cost effective catalytic option has only recently become the focus of considerable interest, in terms of research and development.

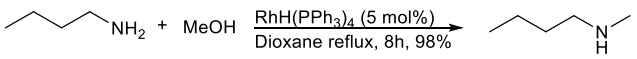


Scheme 32: 'Hydrogen Borrowing' Process

The process displayed in Scheme 32 involves the type of catalysis that will be the focus of this PhD project and will therefore, be used as the main focus of this introduction to 'hydrogen borrowing' chemistry. The sequential process begins with a primary or secondary alcohol, in this case benzyl alcohol, which is oxidised to benzaldehyde by the transfer of two hydrogen atoms to the empty valency iron complex to form the iron hydride species **18**. This step is then followed by the generation of an imine intermediate **59** through the reaction of benzaldehyde with an amine. The final step is the reduction of the imine intermediate **59** through the transfer of two hydrogen atoms from the iron species **18** to the imine intermediate

59 to produce the final desired amine **60**. The final step regenerates the active empty valency iron complex **17** and fulfils the 'hydrogen borrowing' process.

As the 'hydrogen borrowing' methodology involves the *N*-alkylation of amines,[28] that particular type of catalysed reaction has been known with heterogeneous catalyst since the 1920's.[29,30] However, the use of homogeneous catalysis, such as the type of catalysis displayed in Scheme 33, did not appear until 1981, with the publication of the use of a homogeneous rhodium, ruthenium and iridium catalysts for the *N*-alkylation of pyrrolidine and other primary amines.[31] This publication marked a key milestone in the development of homogeneous catalysis of the *N*-alkylation of amines, giving the first case homogeneous 'hydrogen borrowing'.



Scheme 33: First Publication of Homogeneous Catalysed *N*-alkylation Reaction

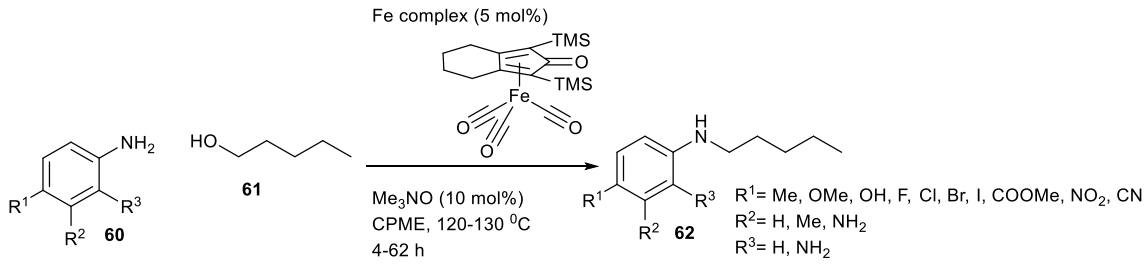
The use of organometallic catalysts for the application of the 'hydrogen borrowing' methodology has received a considerable amount of attention with numerous reports in publications, but the majority of the organometallic complexes being reported are based on precious metals, such as, iridium,[32] ruthenium[33] or palladium.[34]

(1.9) Application of (Cyclopentadienone)Iron Tricarbonyl Complexes to 'Hydrogen Borrowing' Reactions

A number of publications in the past decade have described the use of (cyclopentadienone)iron tricarbonyl complexes as hydrogen transfer catalysts for use in both oxidation and reductions reactions of alcohols, carbonyl and imine groups. The principles of both processes were subsequently combined and this allowed a series of publications to be made regarding the application of this type of iron catalyst to the catalysis of 'hydrogen borrowing' reactions.

As with the majority of published work regarding reduction and oxidation reactions, the iron complex **1** has again proven to be a valuable catalytic option for use in 'hydrogen borrowing' reactions.

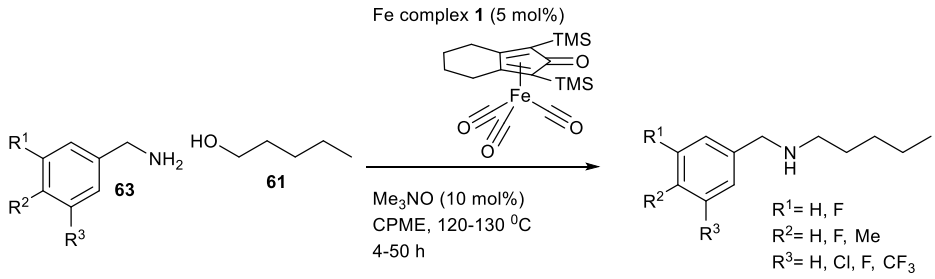
The first example of the application of (cyclopentadienone)iron tricarbonyl complexes to 'hydrogen borrowing' reactions was recently published in 2014 by Feringa et al,[35] which was further supplemented by a subsequent publication in 2016, which detailed numerous advancement in this area of catalysis. The initial publication made a comprehensive overview of possible application of a novel methodology, beginning with a thorough investigation into the *N*-alkylation of aniline-based reagents **60** with 1-pentanol **61**, which produced a significant range of example compounds **62** (Scheme 34).



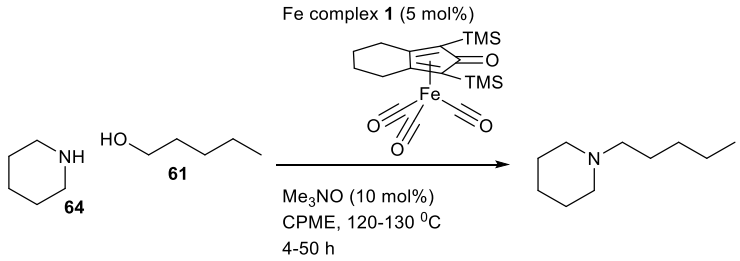
Scheme 34: Reaction Conditions Used by Feringa et al.

This thorough introduction to the application of this type of catalysis was followed by the subsequent application to the *N*-alkylation of a range of benzylamine **63** (Scheme 35) and piperidine-based amines **64** (Scheme 36) with primary alcohols (e.g. 1-pentanol) **61** and more interestingly, dialcohols (e.g. 1,4-butanediol, 1,5-pentanediol and 1,6-hexanediol). The investigation into the use of benzylamines containing halogenated substituents such as fluoro, chloro or trifluoromethyl groups at the 3- or 5- phenyl ring positions, yielded some intriguing results, including the observation that the presence of an electron-withdrawing group on the benzylic ring, increased the reactivity of the amine towards the 'hydrogen borrowing' methodology, in comparison to the observed reactivity of benzylamine under the same reaction conditions. This observed effect caused the reaction yield to increase from 62% to 80%-95%. The use of *p*-methyl substituted benzylamine

also revealed that the presence of an electron-donating group decreases the reactivity of the amine and reduced the yield of the reaction to 30%. Hence, this area was not reported any further.

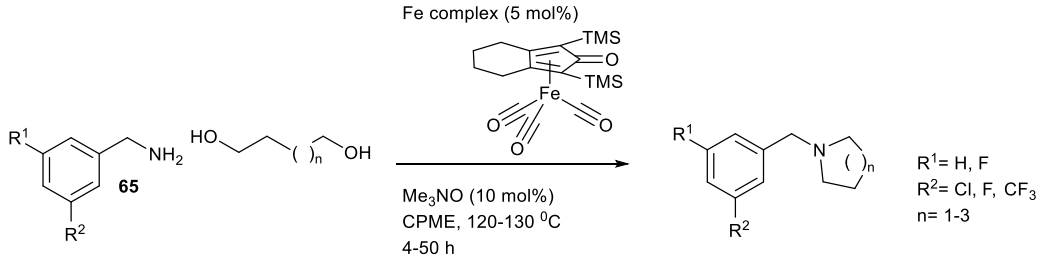


Scheme 35: Use of Benzylamine Derivatives for 'Hydrogen Borrowing' Chemistry



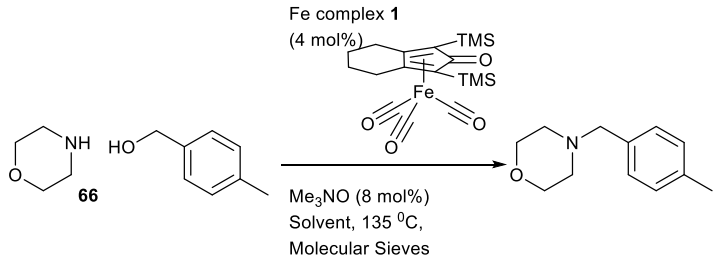
Scheme 36: Use of Piperidine for 'Hydrogen Borrowing' Chemistry

The publication also reported the application of the developed methodology to the use of dialcohols for the synthesis of tertiary cyclic amines, through the use of halogenated benzylamine derivatives **65** (Scheme 37).



Scheme 37: Synthesis of Cyclic Tertiary Amines

The subsequent publication in 2016,[36] detailed further investigative work into the application of the developed 'hydrogen borrowing' methodology to the *N*-alkylation of aliphatic amines (e.g. morpholine, piperidine or piperazine) **66**. The reported work began with an analysis to determine the optimum solvent and temperature conditions for the use of the 'hydrogen borrowing' process with morpholine (Scheme 38). The results of this work revealed that with an elevated temperature of 135 ^{0}C and the use of alternate solvents (e.g. DCE or toluene), the conversion of the reaction could be increased from 39% to an excellent yield of >95%.

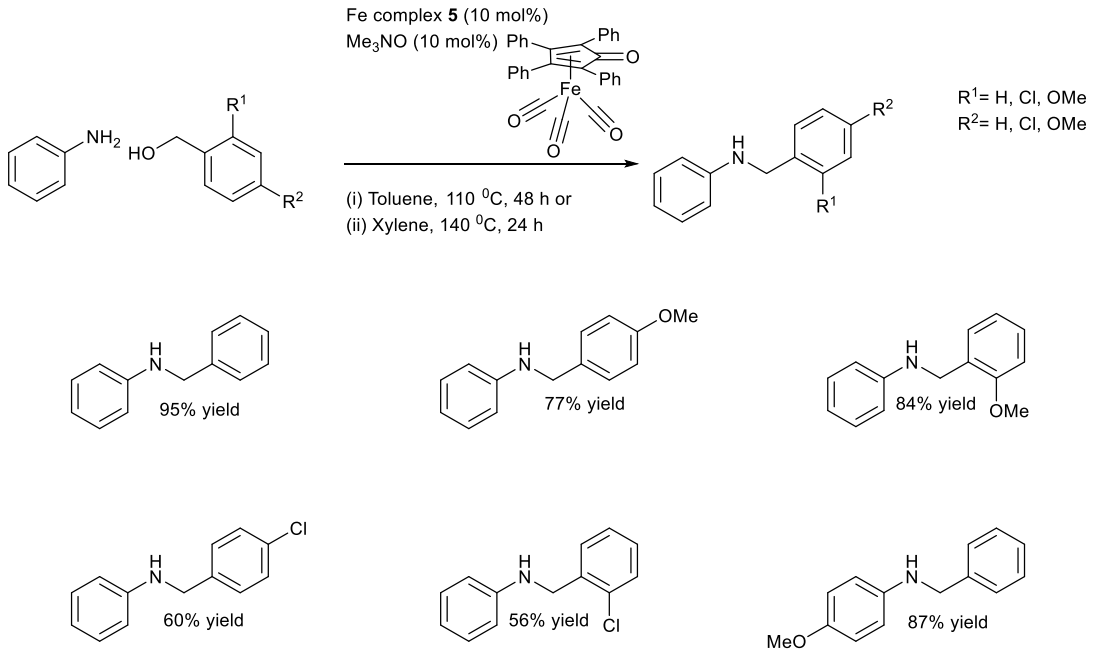


Scheme 38: *N*-alkylation of morpholine

The modified methodology was then applied to the *N*-alkylation to a large range of morpholine, piperidine, piperazine and other aliphatic-based amines with benzylic alcohol- based derivatives.

As the work published in both publications has involved the use of electron-withdrawing groups in either the amine or alcohol starting reagents, the overall results allowed an addition observation of the utilised 'hydrogen borrowing' methodology. The use of electron-withdrawing groups in amines had a positive effect upon the observed reactivity of the associated reagent. However, the observed reactivity of alcohol reagents containing an electron-withdrawing group was negatively affected. A theory was proposed within the publication that the reason behind these observations was the reactivity of the imine intermediate, formed within the 'hydrogen borrowing' process, towards the reduction step to form the desired amine product.

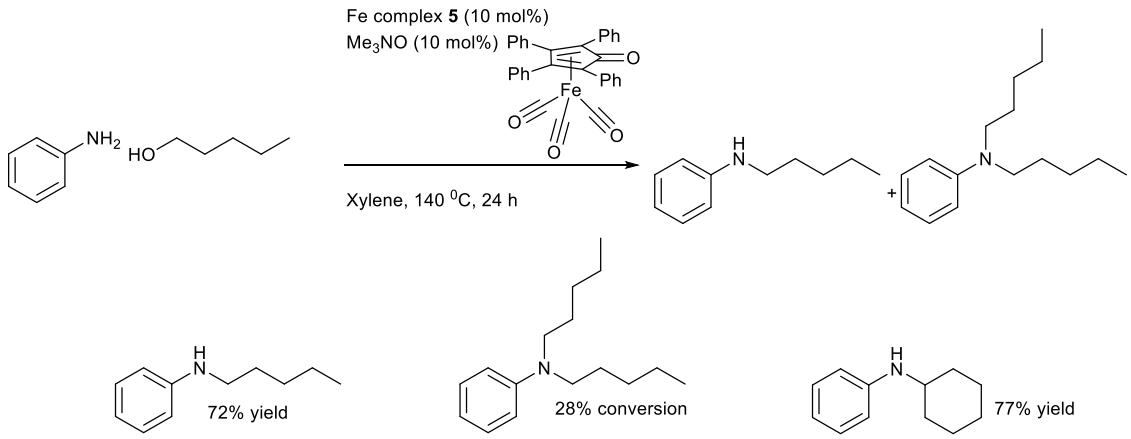
In 2014, a publication by Wills et al,[37] disclosed a piece of work concerning the use of an alternative iron complex **5** for use in 'hydrogen borrowing' chemistry. The work utilised aniline as the amine of interest and a range of benzyl alcohol derivatives and aliphatic alcohols, 1-pentanol and cyclohexanol, were used as the alcohol reagents (Scheme 39).



Scheme 39: Use of Iron Complex 4 For 'Hydrogen Borrowing' Chemistry

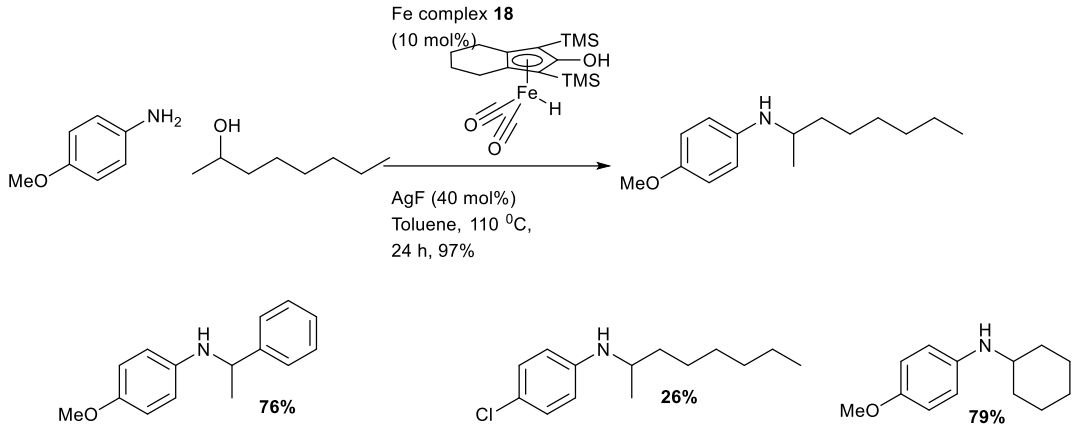
This publication communicated the use *N*-alkylation of aniline to give both secondary and tertiary amine derivatives, through the use of a range of benzyl alcohol derivatives producing secondary alcohols and the aliphatic alcohols producing both secondary and tertiary alcohols. In terms of methodology, reaction conditions set (i) (Scheme 39) could be used for the use of benzyl alcohol, giving a lower reaction temperature of 110 ^{0}C and a longer reaction time of 48 hours. Reaction conditions set (ii) (Scheme 39) were used for the remaining published examples, utilising a change in the reaction solvent, a higher reaction temperature of 140 ^{0}C and a shorter reaction time of 24 hours. These published reaction conditions mirror those used in other previous published work within this area of research and in other publications that would follow.

The application of this methodology to use of aliphatic alcohols (Scheme 40) revealed that the use of a primary aliphatic alcohol (e.g. 1-pentanol) gave a mixture of both secondary and tertiary amine products, with a yield of up to 72% of the secondary amine and a conversion of up to 28% for the tertiary amine. However, with the use of a secondary alcohol (e.g. cyclohexanol), only a secondary amine product was observed with a yield of 77%. There results again mirror what has been observed in other published work.[35]



Scheme 40: Use of Aliphatic Alcohols For 'Hydrogen Borrowing' Chemistry

A publication by Zhao et al,[38] displayed a different approach to the 'hydrogen borrowing' methodology using (cyclopentadienone)iron tricarbonyl complexes (Scheme 41), which involved the use of a Lewis acid to enable the use of secondary alcohols with the methodology. As of when this publication was made, the use of secondary alcohols had not been reported with the associated use of (cyclopentadienone)iron tricarbonyl complexes as the hydrogen transfer catalyst.



Scheme 41: Use of a Lewis Acid For 'Hydrogen Borrowing'

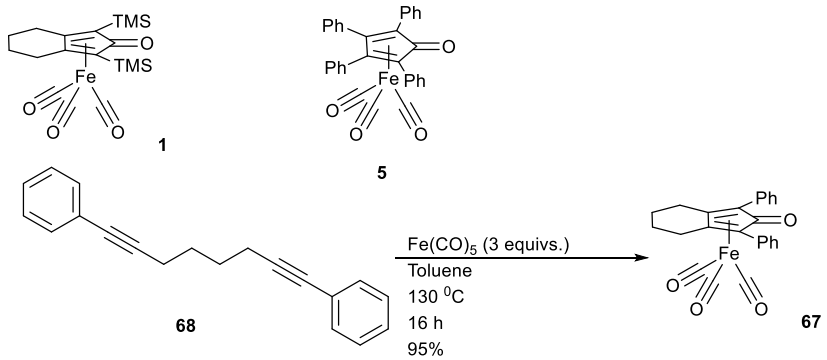
After a thorough testing of a vast array of organic acids (e.g. formic acid, tosic acid or phosphoric acid) and metal salts (e.g. $CuCl_2$, $FeBr_3$, $Ni(acac)_2$ or AgF), the conditions displayed in Scheme 39 were devised with a yield of 97%. These optimised reaction conditions enabled the application of this novel 'hydrogen borrowing' methodology to a number of unsymmetrical secondary alcohols, which were found to be challenging targets with the previously reported methodology.

Results & Discussion

(2.1) Development of 'Borrowing Hydrogen' Conditions

The main topic of research of this project was the development and application of iron-based organometallic complexes to 'hydrogen borrowing' reactions with the potential future application to industrial synthetic work more cost-effective choice for the catalysis of industrial-based reaction. With the high prices of more precious metals, such as, palladium or platinum, and the significantly lower cost of purchasing iron-based reagents to synthesise iron-based catalysts, research into the application of such catalysts, in this case, those derived from the (cyclopentadienone)iron tricarbonyl structure, has become an area of significant interest.

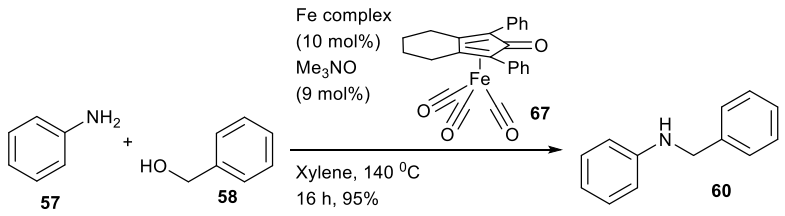
Following on from previous success with 'hydrogen borrowing' methodology in the Wills' group using iron complex **5**,[37] and to extend this type of organometallic catalysis, a new set of catalytic conditions was required with a different iron complex. The study began with the synthesis of iron complex **67** from dialkyne **68**. A secondary purpose of the choice of iron complex was to explore possible improvements to the 'hydrogen borrowing' applications already published using iron complex **1** (Scheme 42).



Scheme 42: Synthesis of Diphenyl Iron Complex

By incorporating the experimental procedures used during past group work[37] and observations obtained from previous work carried out in this PhD project

concerning the use of different equivalents of the trimethylamine *N*-oxide activator, the set of reaction conditions displayed in Scheme 43 were designed. The selection of the 9 mol% equivalent of the activator was made to limit any catalyst decomposition that was suspected to be caused by an excessive level of the activator by the removal of more carbonyl groups from the iron complex structure.



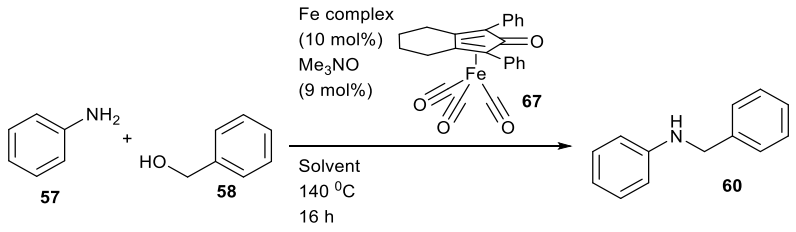
Scheme 43: 'Hydrogen Borrowing' Methodology

The reaction conditions represented in Scheme 43 were then employed for the use of iron complex **67** in 'hydrogen borrowing' between aniline **57** and benzyl alcohol **58** to give *N*-benzylaniline **60**, and resulted in a conversion of 95% after 16 hours. In order to assess the viability of this new set of reaction conditions, the reaction was repeated with iron complexes **1** and **5**, giving conversions of 50% and 60% respectively.

The development of reaction conditions for the reactions shown in Scheme 43 also involved investigations into the ratio of aniline and alcohol used. After carrying out test reactions for three sets of conditions consisting of ratios of 1.5:1, 1:1 and 1:1.5, the results showed that an excess of either reagent was required to drive the reaction forward and the use of a ratio of 1:1 impeded the reaction, resulting in lower conversion. As both sets of reagent ratios gave a similar amount of conversion to product, an excess of amine was selected for use in future reactions, as aniline was the highest polarity component in a reaction mixture and the use of column chromatography to isolate product material was therefore simplified.

To assess the possibility of further improvement to the reaction conversion through the choice of solvent used, a series of different solvents were subsequently tested with the reaction conditions in Scheme 44 for the 'hydrogen borrowing' reaction

between aniline and benzyl alcohol. The solvents screened included toluene, dichloromethane, tetrahydrofuran, cyclopentylmethyl ether, ethyl acetate and diethyl ether.



Scheme 44: Conditions For Assessing Solvent Conditions

Solvent	Conversion/ %
Xylene	95
Toluene	85
Dichloromethane	0
Tetrahydrofuran	87
Cyclopentylmethyl ether	70
Ethyl acetate	85
Diethyl ether	60

Table 2: Table of Results for Solvent Assessment.

The use of pressure tubes to carry out the 'hydrogen borrowing' reactions allowed the use of lower boiling point solvents, such as, diethyl ethyl and the tests of the above solvents gave product conversions of 85%, 0%, 87%, 70%, 85% and 60% respectively (Table 2). The conversions displayed in Table 2 were obtained through ^{1}H NMR analysis of the crude reaction mixtures obtained from the working up of each reaction by passing each reaction contents through a celite filtration plug eluted with ethyl acetate and an overall mass balance was taken in each case to ensure no desired material was left on the celite plug, giving an authentic overview of the reaction outcome. The use of a celite filtration plug was a necessary step to remove paramagnetic iron impurities from the reaction mixtures to allow the ^{1}H

NMR analysis to obtain the reaction conversions by comparison of the relative integration values of the alcohol CH_2 group to the product amine CH_2 group.

The results of the solvent screen supported the use of xylene for further use in subsequent research on 'hydrogen borrowing' reactions and the high conversion percentages for toluene, tetrahydrofuran and ethyl acetate, also represent other options for reaction solvent, providing potential solutions to any future solubility issues.

(2.2) Study of the effect of electronic changes to iron catalysts for 'hydrogen borrowing' reaction – Synthesis of iron complexes

A study into the different electronic environments of (cyclopentadienone)iron tricarbonyl complexes was identified as an area of interest and four iron complexes **69**-**72** were identified to be synthesised, alongside complex **67**. Their structures alongside iron complex **67** would represent a series of electron-rich and electron-poor iron complexes, with respect to **67**, to which their catalytic properties could be compared.

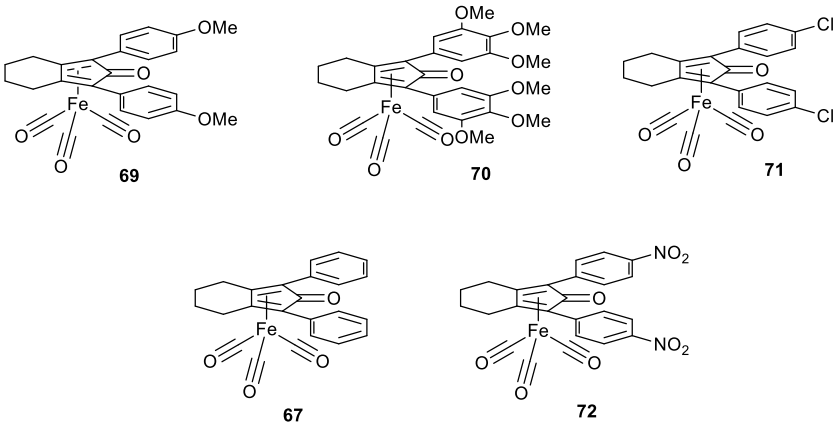
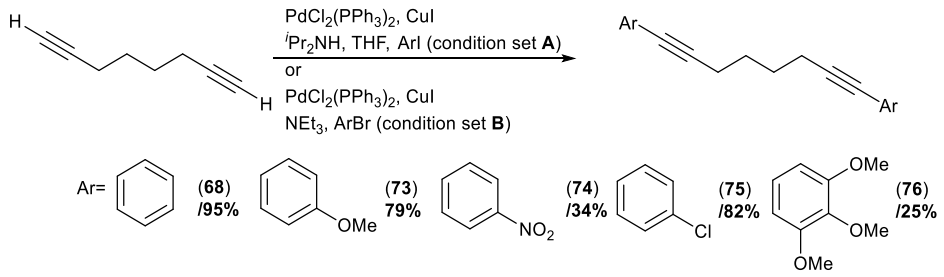


Figure 4: Proposed Structures of Iron Complexes

The synthesis of dialkyne precursors **73**-**75** (Scheme 42) was successfully carried out using conditions set **A** (Scheme 45) from 1,7-octadiyne and aryl iodides, giving

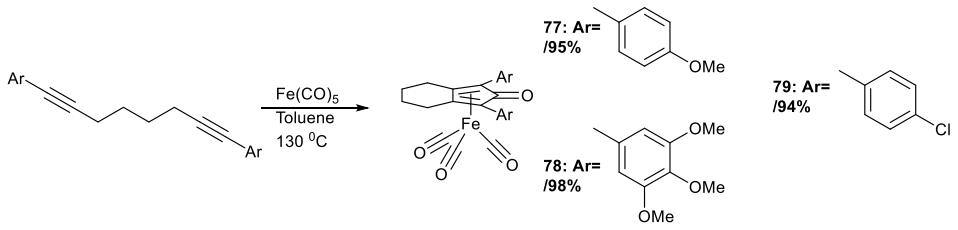
products in yields of 64-95%. However, as the goal of this project was the synthesis and use of low cost iron complexes, the use of the corresponding aryl iodide to synthesise dialkyne **76** was not a cost effective option and the decision was made to use 5-bromo-1,2,3-trimethoxybenzene.



Scheme 45: Conditions for Dialkyne Synthesis

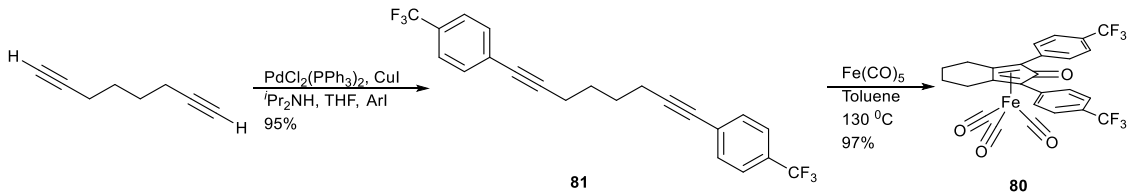
This change of reagent to the use of the 5-bromo-1,2,3-trimethoxybenzene was incompatible with condition set **A**, providing no product formation. Therefore dialkyne **76** was synthesised through the use of a different set of reaction conditions (**B**; Scheme 45), although in a reduced yield of 25%, but as the cost of 5-iodo-1,2,3-trimethoxybenzene was too high to be justified for use in the synthesis of a desired low cost iron complex, the use of 5-bromo-1,2,3-trimethoxy benzene was considered a more cost effective choice. The lower yield associated with the use of an aryl bromide against an aryl iodide in a Sonogashira reaction was likely to be a result of the lower level of reactivity associated with the use of aryl bromides in comparison to the use of aryl iodides.

To ensure ease of iron complex synthesis throughout, iron complexes **77**-**79** were synthesised through the same synthetic procedure as was used for **67** (Scheme 46) and gave products in excellent yields of 70-98%. These syntheses provided a reliable means of producing enoughiron complex material for the project.



Scheme 46: Synthesis of Iron Complexes 69-71

However, iron complex **72** could not be synthesised through the use of the reaction conditions shown in Scheme 46, possibly due to a reaction between Fe(0) and nitro-functional groups, which caused an alternative reaction pathway to ensue, producing no desired iron complex **72** and no recovery of starting material. Due to the failed reaction pathway, the new target iron complex **80** was identified, to be synthesised from dialkyne **81** (Scheme 47). Dialkyne **81** and iron complex **80** were successfully synthesised through Scheme **44**, obtaining yields of 95% and 97%, respectively.



Scheme 47: Synthesis of CF_3-substituted Iron Complex 80

Through establishing the reaction pathways as described in Schemes 42 and 45-47, an efficient method of synthesising sufficient quantities of the five iron complexes **67**, **69**-**71** and **80**, was obtained and allowed a constant supply of the iron complexes without significant impact on throughput of 'hydrogen borrowing' result

(2.3) 'Hydrogen borrowing' – Investigation of changes to alcohol carbon chain length and electronic environment of iron complex

Using the observations made in previous work carried out during this project, the hypothesis was made that the reactivity of a cyclopentadienyl iron complex to oxidation and reduction reactions is related to the acidity of the hydroxy functional group of the activated iron-hydride complex. The decision was made to study this hypothesis by varying the electron environment of the hydroxy group by varying the substituents on the aromatic rings of the cyclopentadienone structures, from electronegative trifluoromethyl group to electron-rich 3,4,5-trimethoxy substituents.

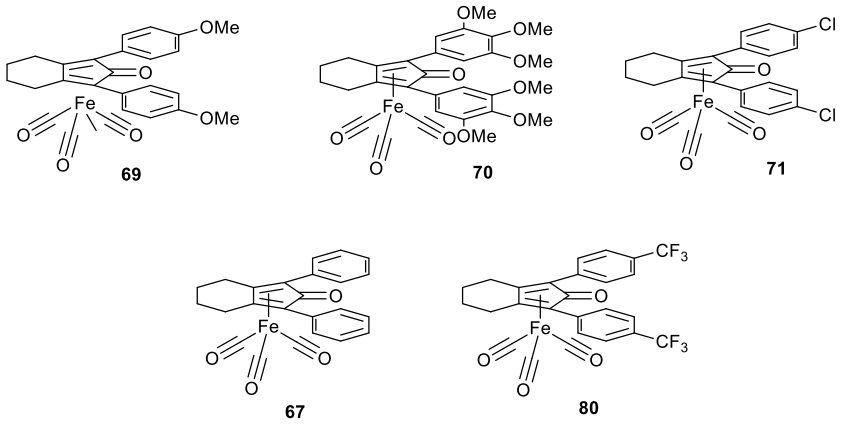


Figure 5: Structures of Iron Complexes Used in Study of Electronic Environments

To investigate the effect of making such alterations to the electronic state of the iron catalyst on the reactivity towards the reaction shown in Scheme 40, the reaction was repeated using all five iron complexes **67**, **69**-**71** and **80** (Figure 5). However, no overall trend could be established from the obtained reaction conversions (Table 2) with the use of benzyl alcohol and aniline as the starting reagents. The only observation to note was that changing the iron complex substituents to *para*-methoxy **69** or *para*-chloro **71** substituted phenyl rings decreased the reaction conversions to 60% and 66% respectively. These results would suggest that increasing or decreasing electron density on the aromatic rings, with respect to iron complex **67**, inhibits the 'hydrogen borrowing' mechanism by

reducing the reaction rate of an unknown part of the catalysis cycle. However, the use of iron complexes **70** and **80**, which possess larger electron-rich and electron-poor environments than the previous two iron complexes **69** and **71**, gave reaction conversions of 91% and 87%, respectively.

The 'hydrogen borrowing' mechanism is heavily reliant on the ability of the iron complex to oxidise the alcohol starting material to the corresponding carbonyl-containing compound (Figure 6). The imine-formation reaction step is then able to proceed through a condensation reaction with the amine starting material and reduction of the imine functional group then proceeds via the iron-hydride catalyst.

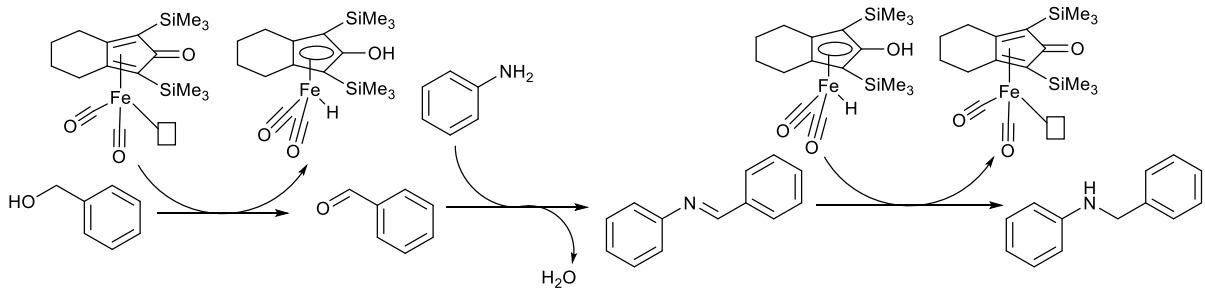


Figure 6. Reaction mechanism for hydrogen borrowing.

With this proposed reaction pathway in mind, the difference in reaction conversions described previously was hypothesised to have been a result of the oxidation and reduction potentials of the five iron complexes and any change to the rates of reaction to the corresponding steps of the catalytic cycle. However, due to the paramagnetic nature of the activated iron complex, further investigation of the catalytic cycle through NMR spectroscopy was not possible and as the reaction is performed under inert conditions in a pressure tube to avoid catalyst degradation, reaction sampling was also made more difficult and not practical with the current methodology.

To extend the electronic study and obtain more information on the 'hydrogen borrowing' methodology, the study was then extended to include extending the 'CH_2' chain length in the alcohol from benzyl alcohol, up to 4-phenylbutan-1-ol and observe any trends that emerged (Table 3).

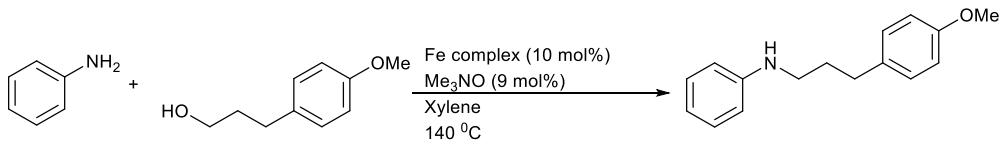
However, the reaction conversions using iron complexes **67**, **69**-**71** and **80** with the use of the four alcohols of increasing carbon chain length, revealed no overall increasing or decreasing trends. The set of results obtained from this work included numerous data points, which did not follow any observed trends with unexpectedly low conversion values, which had no clear explanation and were hypothesised to have been caused by improper stirring of the reaction vessels, producing potential inconsistency. The hypothesis was proven to be incorrect when all results in Table 3 were repeated to ensure the conversion percentages were consistent results of the methodology being used and no explanation was observed for the lack of any general trends.

For the majority of the iron complexes being used, the results displayed no general ascending or descending trend in reaction conversion with increasing carbon chain length from benzyl alcohol to 2-phenylethanol, 3-phenylpropan-1-ol and 4-phenylbutan-1-ol respectively. With the use of complexes **69**, **70** and **80**, increases in reaction conversion were observed with increasing carbon chain length to 2-phenylethanol and no clear explanation could be deduced for the reduction in conversion observed with the use of complexes **67** and **71**.

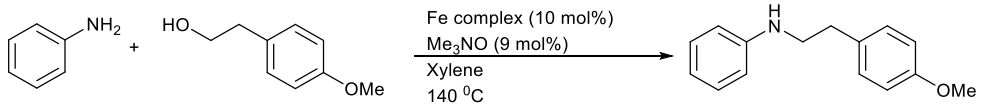
The use of 3-phenylpropan-1-ol gave a distinct reduction in conversion of 40%-59% with iron complexes **67**, **69**, **70** and **80**. With such a trend in conversion, 3-phenylpropan-1-ol was shown to be less suitable for 'hydrogen borrowing' reactions with aniline and a hypothesis was formed that further increases in the carbon chain length to 4-phenylbutan-1-ol would further decrease reaction conversion. However, significant increases in reaction conversion were observed with four of the iron complexes (Table 3).

Although no specific trends could be deduced from the study of carbon chain length against changes to the electronic environment of the iron complex, the overall methodology being used was shown to give excellent yield of above 70% in the majority of reactions. Two *para*-methoxy substituted alcohols were selected for use with the five iron complexes, to explore any effects caused by the use of alcohols with more electron rich aromatic groups, 3-(4-methoxyphenyl)propan-1-ol **82** and

4-methoxyphenethyl alcohol **83** (Schemes 48 & 49), to give amines **84** and **85**, respectively.



Scheme 48: Use of Substituted Alcohol 82 in Table 2.



Scheme 49: Use of Substituted Alcohol 83 in Table 2.

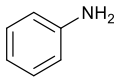
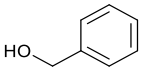
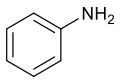
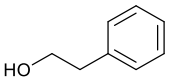
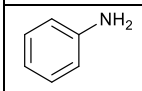
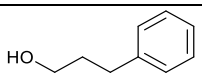
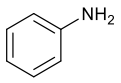
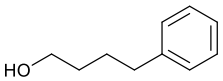
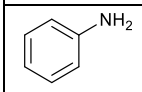
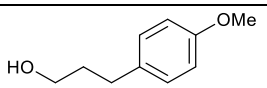
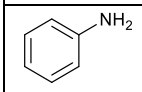
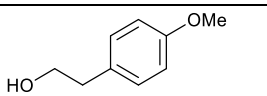
		Iron Complexes				
Amine	**Alcohol**	**No. 67**	**No. 69**	**No. 70**	**No. 71**	**No. 80**
		**90**	**60**	**91**	**66**	**87**
		**79**	**90**	**95**	**55**	**100**
		**20**	**50**	**50**	**80**	**55**
		**90**	**70**	**30**	**72**	**100**
		**30**	**100**	**100**	**100**	**100**
		**60**	**100**	**60**	**40**	**60**

Table 3: Table of Conversions For 'Hydrogen Borrowing' Reactions

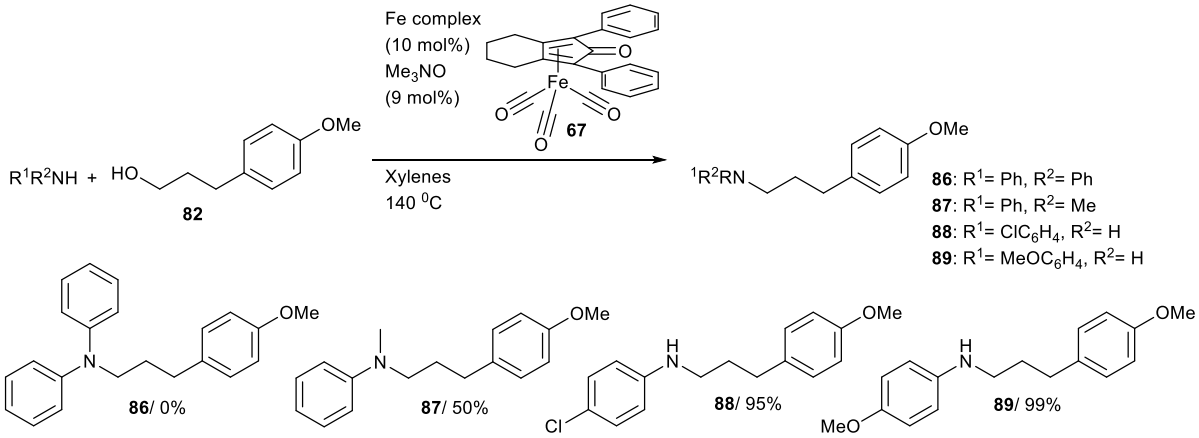
3-(4-Methoxyphenyl)propan-1-ol **82** was used in a 'hydrogen borrowing' reaction with aniline using iron complexes **67**, **69**-**71** and **80**. The results of these five reactions showed alcohol **82** to be highly suitable for use with the four substituted iron complexes, giving full reaction conversions with no remaining alcohol starting reagent after 16 hours. However, when the diphenyl iron complex **67** was used, only 30% conversion was observed after 16 hours.

The use of 4-methoxyphenethyl alcohol **83** was the final part of the aforementioned study and gave conversions to product of 40-60% for most of the iron complexes. Only with the use of the bis methoxy substituted iron complex **69** was full conversion observed.

The results for the use of methoxy substituted alcohols **82** and **83** suggest that the use of such a type of alcohol with a three carbon chain length is highly suitable with the use of (cyclopentadienone)iron tricarbonyl complexes with aryl substituents and reducing the carbon chain length of the alcohol can have a negative effect on reaction conversion.

(2.4) Expanding Amine Use to Other Aniline-Based Amines

An attempt was now made to expand the scope of the 'hydrogen borrowing' methodology to other aniline-based amines. 3-(4-methoxyphenyl)propan-1-ol **82** was selected as the alcohol to be used with four amines; diphenylamine, *N*-methylaniline, 4-chloroaniline and *p*-anisidine (Scheme 50), due to the alcohol possessing the optimal performance in previously completed work.



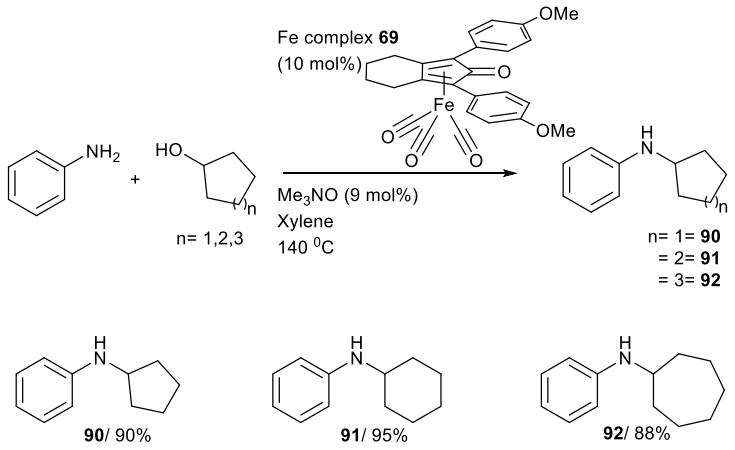
Scheme 50: Use of 'hydrogen borrowing' methodology for aniline derivatives

The attempted synthesis of amine **86** gave no desired product and only starting reagents remained after the reaction time had expired. Possible causes for this outcome are the increased steric bulk associated with two phenyl rings and/or the change of pK_a with using diphenylamine against aniline. The synthesise of **87**-**89** was successfully carried out with yields of 50, 95 and 99%, respectively.

As amines **88** and **89** were both synthesised through reactions which proceeded in full conversion with the use of primary amines, 4-chloroaniline and *p*-anisidine, respectively. Amine **86** was produced from a secondary amine, *N*-methylaniline, in a lower yield of 50%, these results suggested that the use of secondary aniline-based amines gives reactions with slower reaction rates.

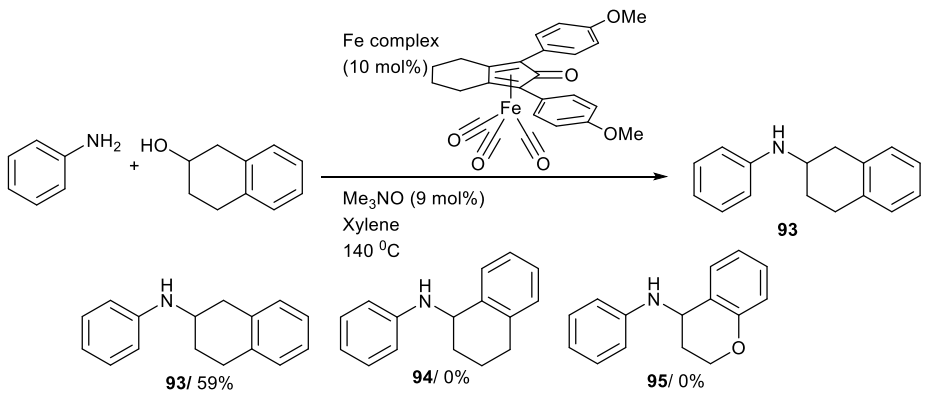
(2.5) Investigation into the Use of Secondary Alcohols with Aniline for 'Hydrogen Borrowing' Reactions

With work completed on the electronic study, research on 'hydrogen borrowing' methodology was extended to include secondary alcohols. The first result with the use of a cyclic secondary alcohol was with cyclohexanol to give amine **91** as the product of the reaction and this was achieved with full conversion and an excellent isolated yield of 95%. The results on the use of cyclic aliphatic secondary alcohols were then extended to the use of cyclopentanol and cycloheptanol, obtaining amines **90** and **92** with isolated yields of 90% and 88%, respectively (Scheme 51).



Scheme 51: The Use of Secondary Cyclic Aliphatic Alcohols

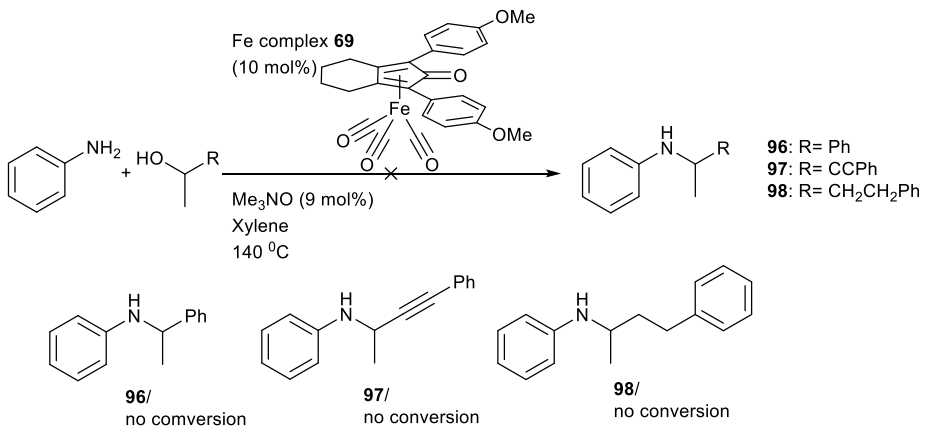
The three examples for the use of cyclic aliphatic secondary alcohols demonstrated high applicability to the 'hydrogen borrowing methodology and the direction of work focused on expanding the product scope. Amine **93** was successfully synthesised from β-tetralone in an isolated yield of 46% with an overall reaction conversion of 59% and an extended reaction time of 40 hours (Scheme 52). Extending the reaction time further made no improvements to reaction conversion and demonstrated that the presence of the aromatic ring within the aliphatic ring of tetralone retarded the 'hydrogen borrowing' reaction. The presence of paramagnetic species in active reaction mixtures made further investigation into this reaction through NMR spectroscopy, impossible.



Scheme 52: Use of Secondary Alcohol Targets For 'Hydrogen Borrowing' Chemistry

Despite the success in the synthesis of **93**, no product was obtained from the attempted synthesis of amines **94** and **95**, as the analysis of the reaction mixtures only revealed the presence of the ketone oxidation product of the alcohol starting reagent and there was no conversion to the desired final amine product. The presence of ketone revealed that the first step of the catalytic cycle was occurring and oxidising the alcohol starting material. However, as no imine compound could be observed, the cause of the failed reactions could be hypothesised to be the imine formation step and the ketones being produced were unsuitable for the condensation reaction with aniline. As there was no source of hydrogen acceptor compound in the mixture, there was no route for the iron-hydride complex to lose a hydrogen pair, to reform the active catalytic species, i.e. the oxidation step used up the active empty valency iron complex, and no further catalytic reaction could take place.

The synthesis of amines **96**-**98** was also unsuccessful (Scheme 53) and no products were isolated. Only starting reagents were observed after the reaction time had concluded and revealed that the cause of the failed reactions was the activated iron complexes were unable to oxidise the alcohol starting reagents.

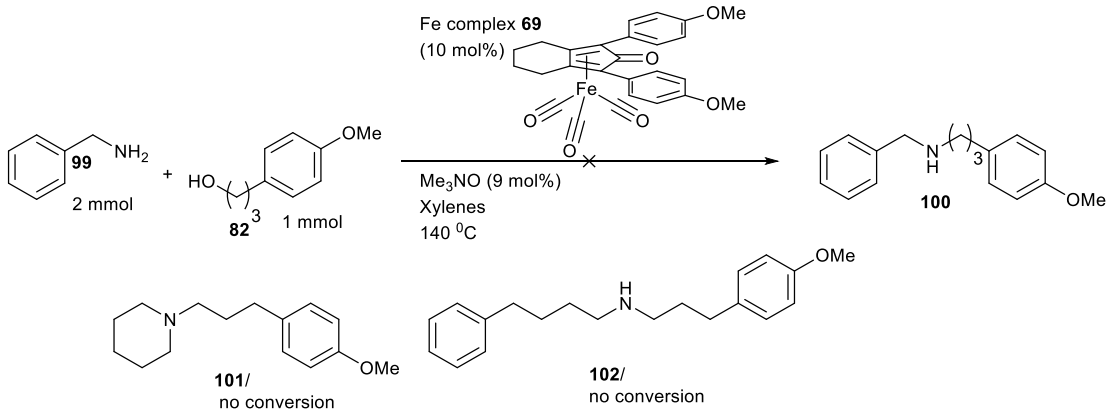


Scheme 53: Use of Other Examples of Secondary Alcohols For 'Hydrogen Borrowing' Chemistry

The results obtained revealed that cyclic aliphatic secondary alcohols were excellent reagent choices for 'hydrogen borrowing' reactions and gave quantitative yields. β-tetralone was also shown to be a suitable reagent. However, the use of other types of secondary alcohols was found to be non-viable with oxidation issues or no imine formation (Schemes 52 & 53).

(2.6) The Use of Aliphatic Amines and Benzylamines

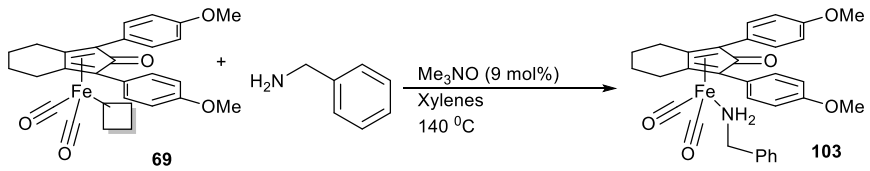
With research completed on the use of aniline-based amines, attention turned to the potential use of benzylamine **99** or piperidine in 'borrowing hydrogen' reactions. The initial attempts towards the use of benzylamine employed the same set of reaction conditions as with earlier work on aniline (Scheme 54) and gave no conversion to amine **100**, while using 3-(4-methoxyphenyl)propan-1-ol 82. The synthesis of amines **101** and **102** was then attempted with the same catalytic conditions from piperidine and 4-phenylbutylamine, respectively. These attempts also gave no conversion to the desired amine product.



Scheme 54: Unsuccessful Synthetic Attempts With the 'Hydrogen Borrowing' Methodology

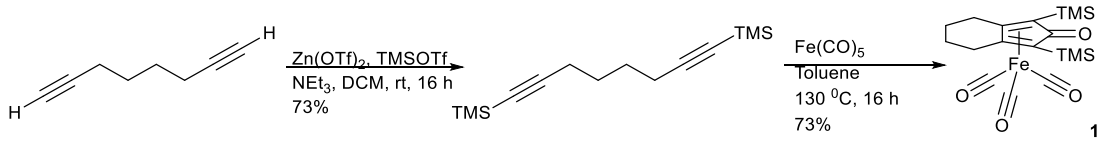
Possible causes for the failed synthetic attempts are i) the iron complex being used (Scheme 54) was unsuitable for use with these different types of amine, ii) the level of iron complex activation with an activator amount of 9 mol% being insufficient to generate an adequate amount of active catalytic iron species or iii) the basic characteristics of the different amines interfering with the catalyst. The reaction conditions used in Scheme 51 were successful with the use of aniline, which has a low basicity with a protonated pk_a value of ~4.6 and amine, such as, piperidine and benzylamine have higher pk_a values of ~10. As the conditions displayed in Scheme 54 also include a 1 mmol excess of the amine and when these conditions are extended to the use of piperidine of benzylamine, the catalytic cycle could be

halted by large amount of basic material occupying the empty valency on the activated iron complex **69** (Scheme 55) to give an amine-conjugated iron complex 101 This hypothesis was supported during reaction analysis with mass spectrometry with observed signal of 566, which is consistent with the theoretical value for the iron complex **103**, in the form of a $(M+H)^+$ ion peak. However, this complex could not be isolated through standard isolation methods such as column chromatography. This results mirrored observations displayed in previous publications by Wills et al[37] and by Beller et al.[16]



Scheme 55: Potential Source of Inhibition With Benzylamine

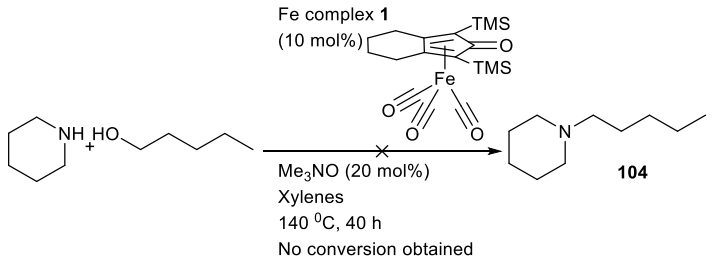
To counteract the effects of this, the ratio of the amine and alcohol reagents were altered to use an excess of the alcohol starting reagent and the iron complex was also changed to iron complex **1**, as this complex possessed known activity towards 'hydrogen borrowing' reactions and was easily accessible synthetically (Scheme 56). The difficulties with the use of iron complexes **67**, **69**-**71** and **80** couldn't be overcome, even at later stages of the project. Iron complex **1** could be easily obtained from this synthetic procedure, as each step only required a straightforward column chromatography procedure to isolate each product. The previous synthesis of the iron complexes **67**, **69**-**71** and **80** was more time consuming.



Scheme 56: Synthesis of Iron Complex 1

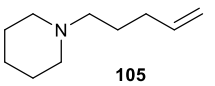
Following the observation of mass spectrometry signals corresponding to the unactivated iron complex, the amount of trimethylamine n-oxide was also increased from 9 mol% to 20 mol% to ensure full activation of available iron complex. This increase in activator was made possible by the change of iron complex due to past use of complex **1** observed less decomposition issues than with iron complex **67**. No change to the solvent used was to be made as no indication of solubility issues was observed.

With the use of the new set of reaction conditions, a reaction was attempted between piperidine and pentan-1-ol (Scheme 57). Analysis of the reaction mixture after the reaction time had expired revealed no residue of piperidine and a mixture of remaining pentan-1-ol, leftover iron complex-related material and a final component, which corresponded to amine **104** under mass spec and TLC analysis. However, amine **104** could not be isolated due to possible volatility issues.

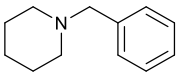


Scheme 57: Attempted Use of Piperidine

To further probe how viable these reaction conditions are, the synthesis of amines **105** and **106** was subsequently attempted. However, amine **105** also presented the same isolation issues and was only clearly observed through TLC and mass spectrometry analysis. Amine **106** was observed to have been synthesised by NMR and mass spectrometry in the reaction mixture. However, the new reaction conditions had created an issue with the use of benzyl alcohol for the 'hydrogen borrowing' reactions, the formation of dibenzyl ether from the remaining benzyl alcohol. This outcome can be theorised to have been caused by the high temperature and pH conditions. Amine **106** could only be isolated in a mixture with dibenzyl ether.

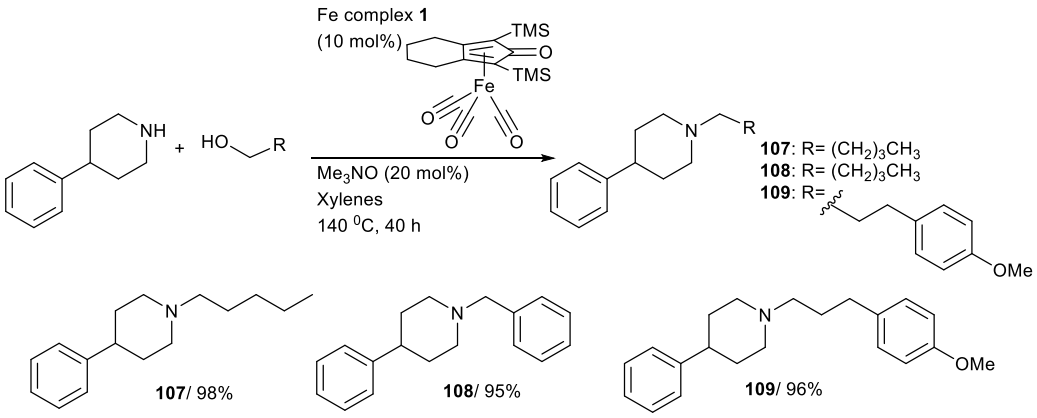


105



106

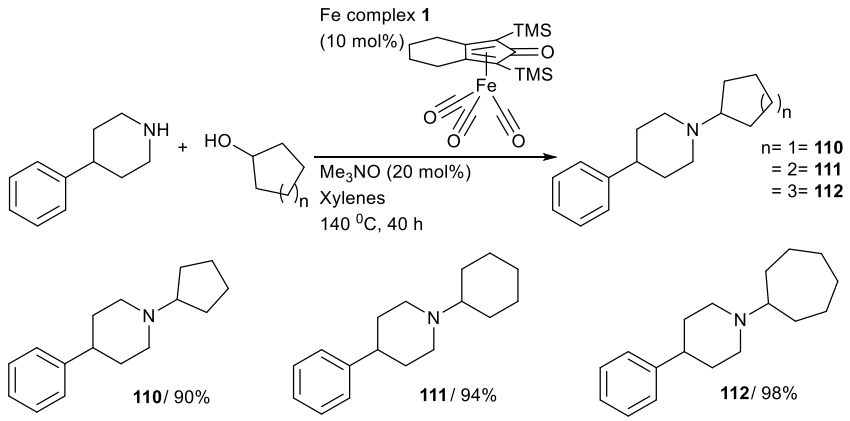
To isolate piperidine derivatives, 4-phenylpiperidine was identified as a potential starting reagent, as the extra phenyl ring may allow isolation of any product compounds without any volatility issues and for additional reaction analysis via UV TLC analysis. In the event, product amines **107**-**109** were synthesised with excellent isolated yields of 98, 95, and 96%, respectively (Scheme 58). The amines were synthesised in a slower, but cleaner pathway, than any amines derived from aniline and no 4-phenylpiperidine was observed after a reaction time of 40 hours. The larger mass of trimethylamine n-oxide used ensured full activation of the iron complex present and the air instability of the activated iron complex caused all catalytic iron species to decompose upon reaction work up, producing only low polarity impurities to remain in the crude reaction mixture. As the product amines **107**-**109** were of higher polarity than any iron catalyst derived impurities and residue alcohol reagent, the product amines were easily isolated through column chromatography, as the most polar component.



Scheme 58: Use of 4-Phenylpiperidine

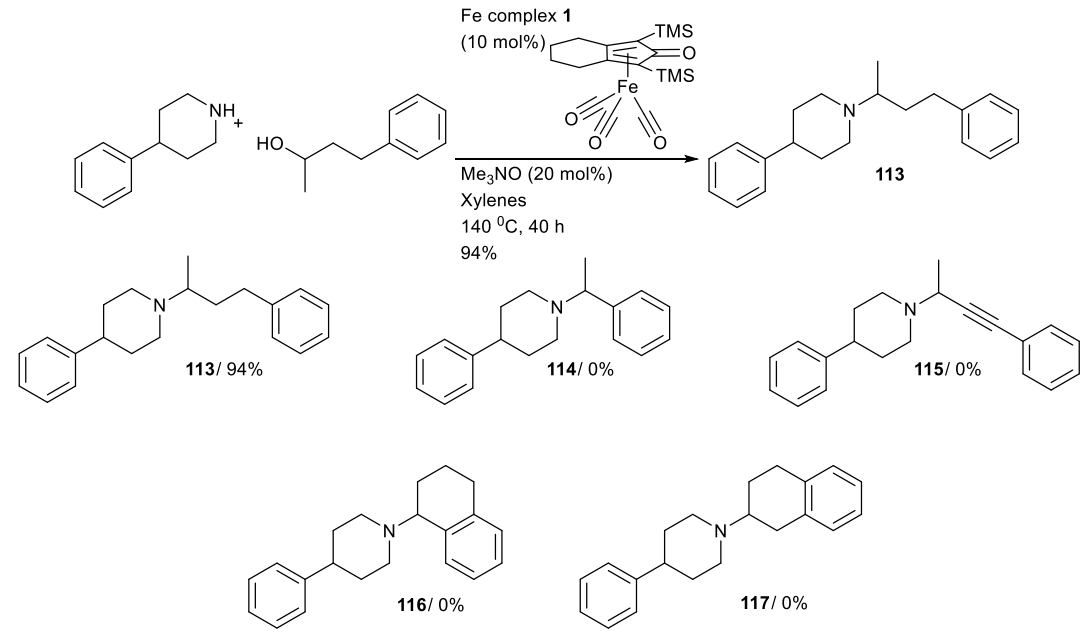
The use of 4-phenylpiperidine was then extended to reactions with cyclic secondary aliphatic alcohols cyclopentanol, cyclohexanol and cycloheptanol under the same reaction conditions, giving amines **110**-**112** with good yields of 90, 94 and 98%, respectively (Scheme 59). These results demonstrated that cyclic secondary

aliphatic alcohols were suitable for 'hydrogen borrowing' reactions with more basic aliphatic amines, not just aniline alone.



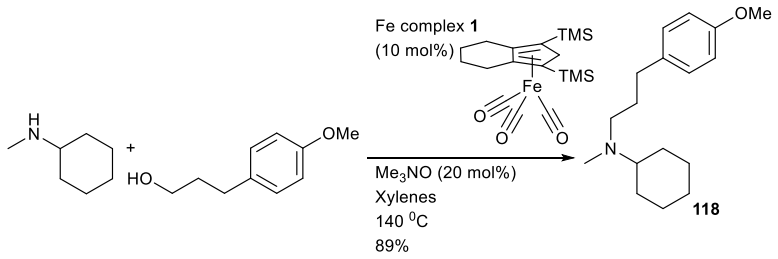
Scheme 59: Use of 4-Phenylpiperidine With Cyclic Secondary Alcohols

In addition to this application, the application of an aliphatic non-cyclic alcohol, 4-phenylbutan-2-ol, was also used to synthesise amine **113** in a good yield of 94% (Scheme 60). The reaction was not possible with the use of aniline as the starting reagent, possibly caused by the lower basicity of aniline. However, the attempted synthesis of amines **114**-**117** was unsuccessful, which demonstrated in a similar case to the use of aniline, secondary cyclic or acyclic benzylic/propargylic alcohols, 1-phenylethanol, 4-phenyl-3-butyn-2-ol and α-tetralol, are not suitable for the desired 'hydrogen borrowing' reactions. In the case of amine **117**, the use of β-tetralol did not give a clear outcome, as paramagnetic impurities made NMR analysis difficult and no clear result was obtained from mass spectrometry.

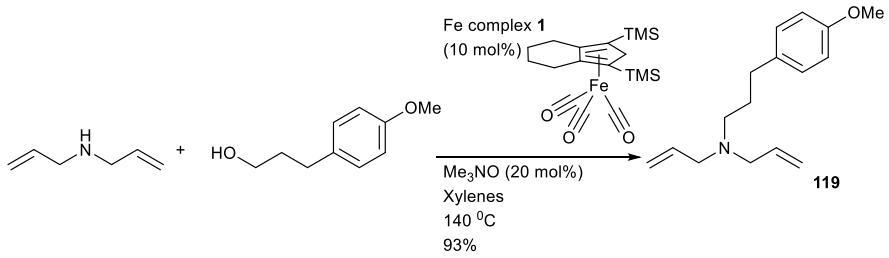


Scheme 60: Attempts With the Use of Secondary Alcohols

The use of secondary amines was further extended to *N*-methylcyclohexylamine (Scheme 61) and diallylamine (Scheme 62). Tertiary amine **118** was produced in a good yield of 89%. The synthesis of amine **119**, achieiving an excellent isolated yield of 93%, demonstrated the application of the 'hydrogen borrowing' methodology to producing tertiary amines with pre-designed functionality towards other types of chemical reactions. In this case, the dialkene functionality provides potential uses for multiple reaction pathways such as metathesis reactions to build more complex compounds.

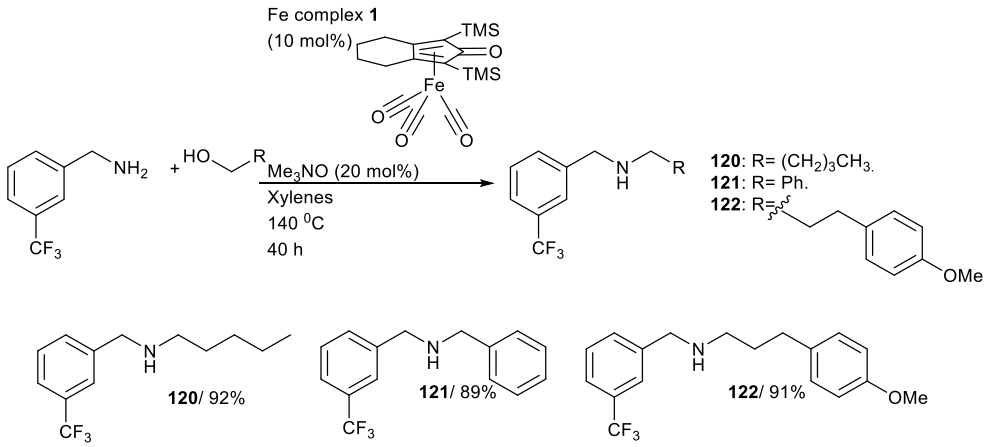


Scheme 61: Use of *N*-methylcyclohexylamine



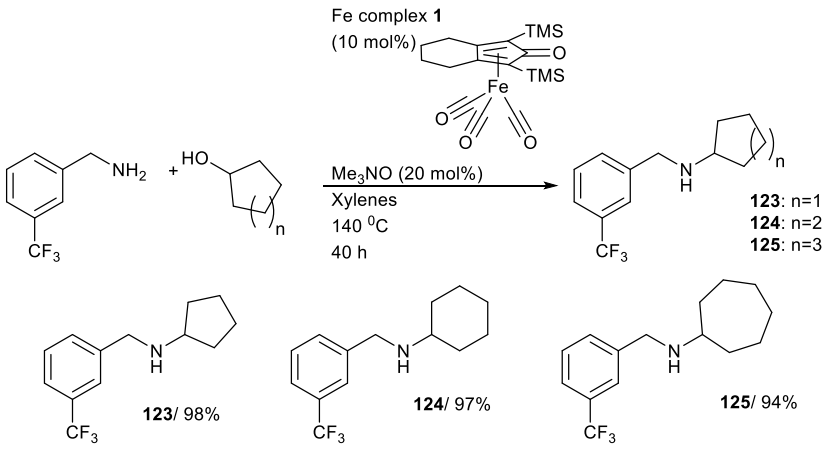
Scheme 62: Application to the Use of Diallylamine

Alongside the synthesis of amines derived from 4-phenylpiperidine, based upon the earlier result on the use of benzylamine with pentan-1-ol, work on benzylamine derivatives was further explored and involved the use of 3-(trifluoromethyl)benzylamine (Scheme 63).



Scheme 63: Uses of 3-(trifluoromethyl)benzylamine

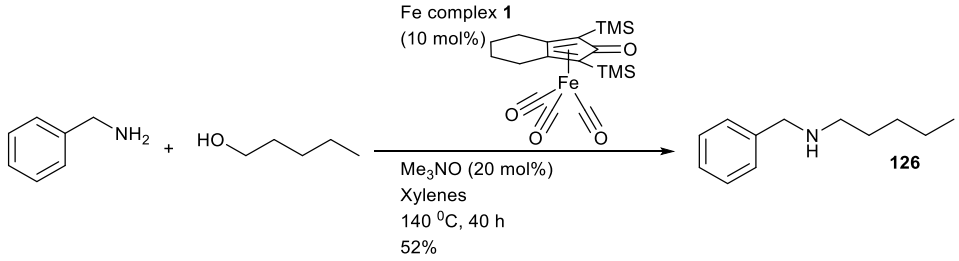
Secondary amines **120**-**122** were synthesised through the use of primary alcohols pentan-1-ol, 3-(4-methoxyphenyl)propan-1-ol and benzyl alcohol in good yields of 92, 91 and 87%, respectively. These results demonstrated a significant increase in reaction yield in comparison with the use of benzylamine and supported the reported effect of using CF_3-substituted benzylamine to reduce the electron density in the benzylamine reagent.[35]



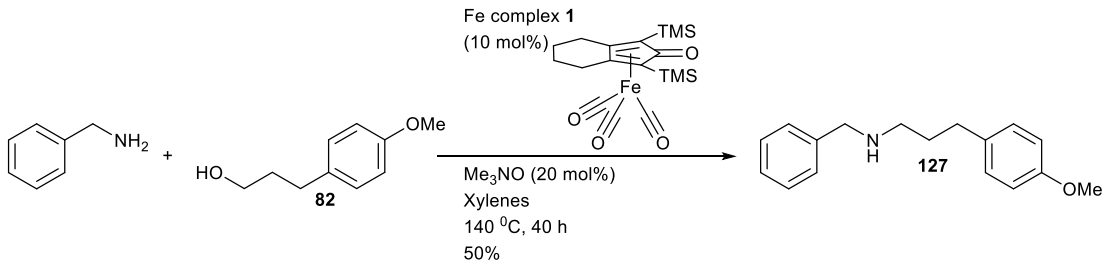
Scheme 64: Use of 3-(trifluoromethyl)benzylamine With Aliphatic Cyclic Secondary Alcohols

The use of secondary alcohols to synthesise secondary amines **123**-**125** was then investigated (Scheme 64) and was found to complete successfully with similar activity as with the use of 4-phenylpiperidine, with good yields of 98, 97 and 94%, respectively. As with the use of the primary alcohols, reactions using 3-(trifluoromethyl)benzylamine completed within 40 hours, demonstrating similar reaction rates to the use of 4-phenylpiperidine.

With the success of using 3-(trifluoromethyl)benzylamine, the use of benzylamine was further investigated. Benzylamine was found to only be active in 'hydrogen borrowing' reactions involving primary alcohols; pentan-1-ol and 3-(4-methoxyphenyl)propan-1-ol **82** (Scheme 65 & 66) to give amines **126** and **127**.



Scheme 65: Use of 1-Pentanol With Benzylamine

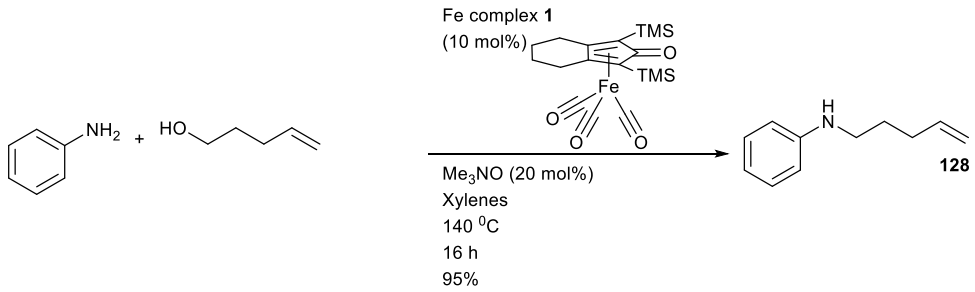


Scheme 66: Use of Benzylamine with (for consistency with Scheme 65).

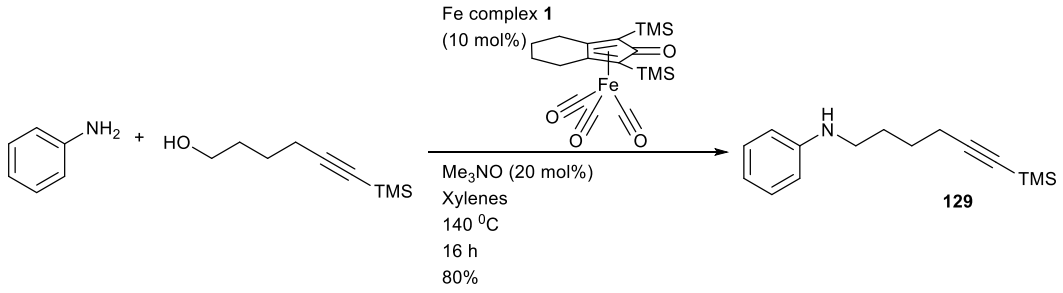
(2.7) 'Hydrogen Borrowing' Reactions to Incorporate Alkene and Alkyne Functional Groups

With work completed on the use of aniline and more basic amines for 'hydrogen borrowing' reactions, research then moved onto incorporating additional functionality into the synthesised secondary and tertiary amines through terminal alkene or TMS-acetylene groups. These types of functional groups could allow the synthesised compounds to possess versatility for further synthetic work to synthesise more complex compounds.

To incorporate such function groups, primary alcohols 4-penten-1-ol and 6-(trimethylsilyl)hex-5-yn-1-ol were used (Scheme 65 & 66). In the initial test reactions, aniline was used as the amine starting reagent, as previous results had shown reaction times could potentially be shorter than with the more basic amines, 4-phenylpiperidine and 3-(trifluoromethyl)benzylamine. Amines **128** and **129** (Scheme 67 & 68) were isolated in good yields of 95% and 80%, respectively, from reactions providing full conversions with no undesired side reactions.

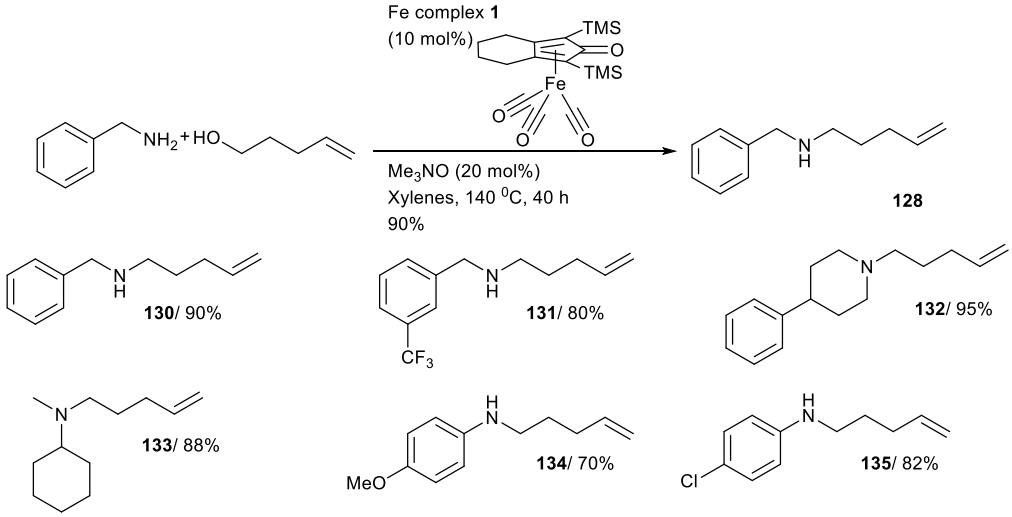


Scheme 67: Use of Alkene-containing Primary Alcohol



Scheme 68: Use of TMS-substituted Alcohol

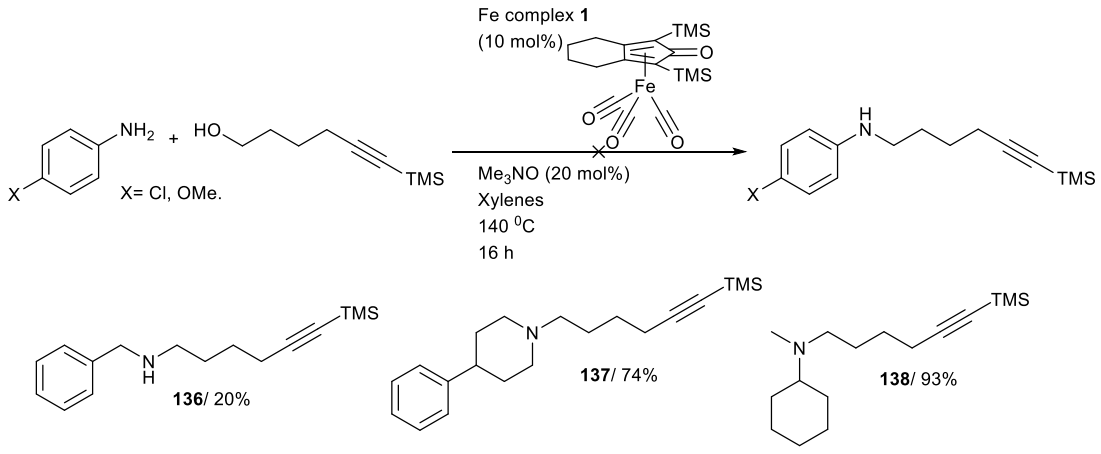
The use of 4-penten-1-ol was subsequently applied to reactions involving a range of more basic amines and other aniline derivatives; benzylamine, 3-(trifluoromethyl)benzylamine, 4-phenylpiperidine, *N*-methylcyclohexylamine, *p*-anisidine and 4-chloroaniline. Secondary amines **130** and **131** were isolated with yields of 90% and 80%, respectively (Scheme 69). However, full conversion was observed with both reaction with analysis of the crude reaction materials, but these results still contradict previous observations with the use of benzylamine, as a lower reaction conversion was expected for the synthesis of amine **130**. The high conversion to **130** would suggest that the use of 4-penten-1-ol must have a positive effect upon the rate of the reaction to give such an outcome, as identical reaction conditions were used to those previous used in benzylamine-related reactions (Scheme 69).



Scheme 69: Use of 4-penten-1-ol For 'Hydrogen Borrowing' Chemistry

Tertiary and secondary amines **132**-**135** were synthesised under identical reaction conditions giving full reaction conversions and isolated yields of 95, 88, 70 and 82%, respectively. These results demonstrated that a terminal alkene group could be easily incorporated into a wide range of secondary and tertiary amines, from anilines to more basic amine, such as, piperidines and benzylamines, which provides opportunity for further synthetic options, as alkenes groups can be further converted to give carbonyl groups, epoxides and halogenated groups, to give a few examples.

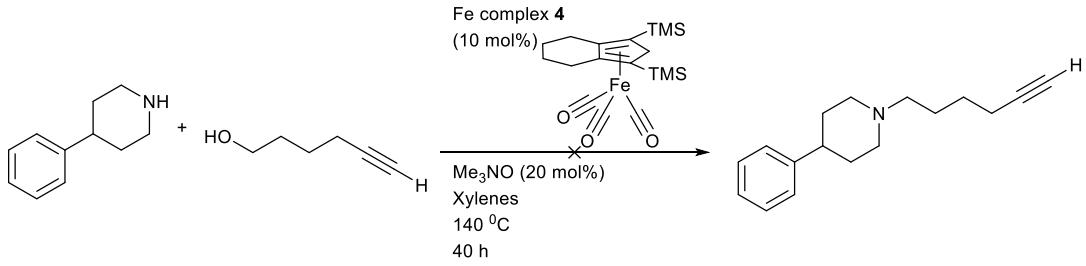
The use of 6-(trimethylsilyl)hex-5-yn-1-ol for 'hydrogen borrowing' reactions was found to be more challenging to be used with aniline derivatives. Although a full conversion was observed with the synthesis of **129**, no conversion was observed with the use of *p*-anisidine and 4-chloroaniline (Scheme 70) and no clear reason was deduced for the lack of reactivity. However, 6-(trimethylsilyl)hex-5-yn-1-ol was found to be suitable for use with more basic primary and secondary amines; benzylamine, 4-phenylpiperidine and *N*-methylcyclohexylamine. Amines **136**-**138** were synthesised with an extended reaction time of 40 hours, same as used in previous work on such types of amine, giving yields of 20, 74 and 93%, respectively. The yield of **136** compliments earlier work with benzylamine giving reduced reaction rates and lower yields.



Scheme 70: Further Use of TMS-substituted Primary Alcohol

Overall, the synthesis of amines **129** and **136**-**138** demonstrates that a TMS-acetylene group can be easily incorporated into a secondary or tertiary amine. Thus, potential synthetic opportunities are now available through subsequent reactions with the alkyne group. One potential synthetic route would be to use desilylation conditions to give a terminal alkyne C-H to perform a Sonogashira reaction.

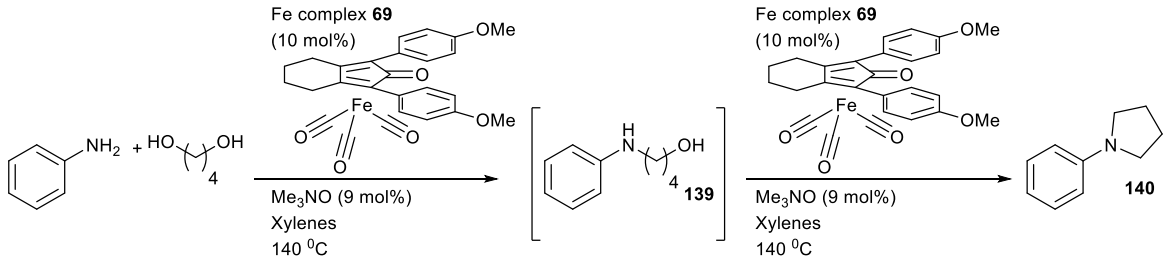
With the viewpoint then of using the 'hydrogen borrowing' to synthesise an amine that could be directly used in a Sonogashira reaction, hex-5-yn-1-ol was used in an attempted reaction with 4-phenylpiperidine (Scheme 71). However, this reaction did not work, no conversion was observed with no observed change to the starting reagents present and alcohols containing an acetylene C-H were assumed to be non-suitable for the methodology being used.



Scheme 71: Failed Use of Unsubstituted Alkynes

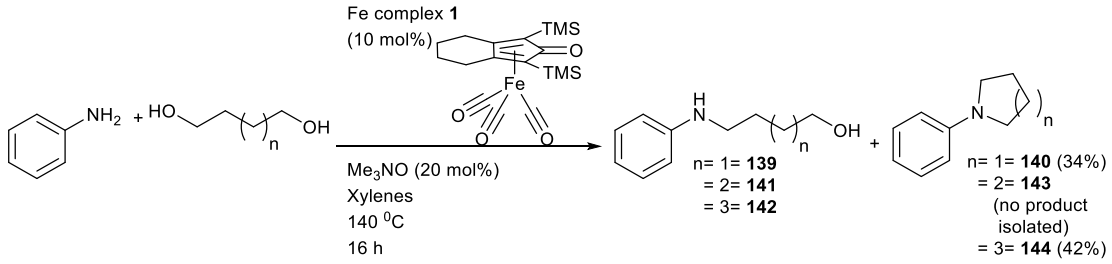
(2.8) The Use of Diols For 'Hydrogen Borrowing' Reactions

The development of reaction conditions for the use of diols for 'hydrogen borrowing' reactions was an area of interest throughout the iron catalysis project. When this set of reaction conditions were designed, the decision was made to use a 1 mmol excess of the diol reagent to the aniline, giving a ratio of 1:2. The reasoning behind this decision was to eliminate the possibility of a double addition of amine onto the diol to give a diamine. The use of excess amine or a 1:1 ratio, was considered to be at risk of this undesired reaction. As the reaction pathway would require the primary amine, in this case aniline, to make two subsequent addition reactions to form the tertiary amine (Scheme 72), the selection of the amine as the limiting reagent was made to drive the production of intermediate **139** (Scheme 72) and the subsequent production of amine **140**.



Scheme 72: Proposed 'Hydrogen Borrowing' Reaction Pathway

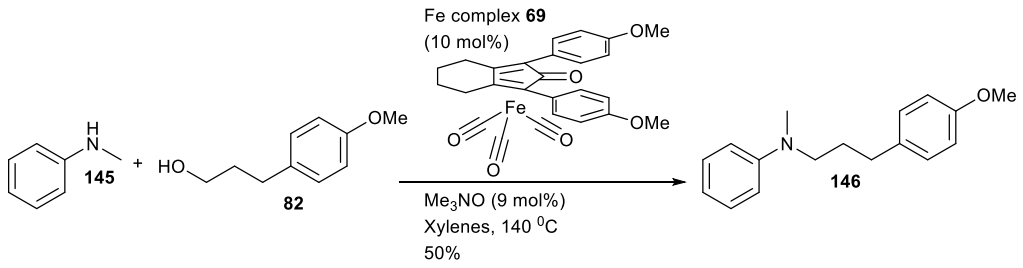
Initial test reactions involved aniline and either butane-1,4-diol, pentane-1,5-diol or hexane-1,6-diol (Scheme 73) and the same reaction conditions as used in earlier project work regarding aniline, giving amino alcohol intermediates **139** and **141**-**142**, and tertiary amines **140** and **143**-**144**. Analysis of the test reactions was found to be difficult due to paramagnetic interference in NMR spectroscopy and the overlapping of proton spectrum peaks associated with both the amino alcohol intermediates and tertiary amine products, causing no reaction conversions to be obtained for either products, for the intermediate compounds. Tertiary amines **140** and **144** were isolated.



Scheme 73: Use of Dialcohols With Aniline

The reaction pathway used was found to possess an issue with the second 'hydrogen borrowing' step (Scheme 72) having a slow reaction rate. The reaction step involves a secondary aniline-based intermediate **139** undergoing an intramolecular reaction to form the tertiary amine **140**, as an example.

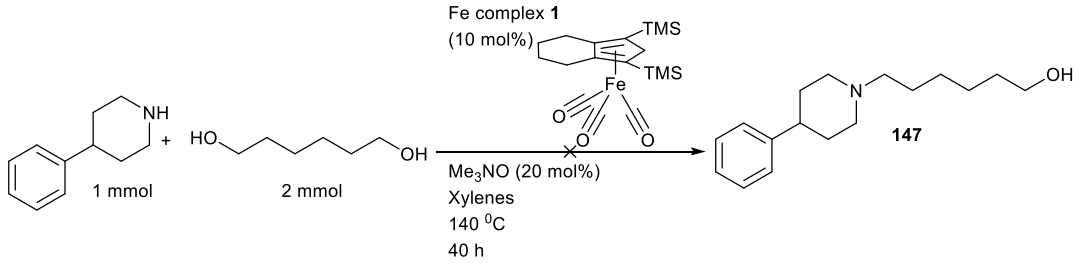
A similar case was observed with the use of the secondary amine, *N*-methylaniline **145** (Scheme 74), which gave a yield of 50% of amine **146** without full conversion in the reaction with 3-(4-methoxyphenyl)propan-1-ol **82.** In contrast, the same alcohol, in the reaction with aniline, gave a the product **83** with an isolated yield of 94% and a full reaction conversion. These observations suggest that the 'hydrogen borrowing' process of converting a secondary aniline derivative to a tertiary amine takes place at a lower reaction rate compared to the conversion of primary to secondary aniline-based amines.



Scheme 74: Use of *N*-methylaniline in 'Hydrogen Borrowing' Reactions

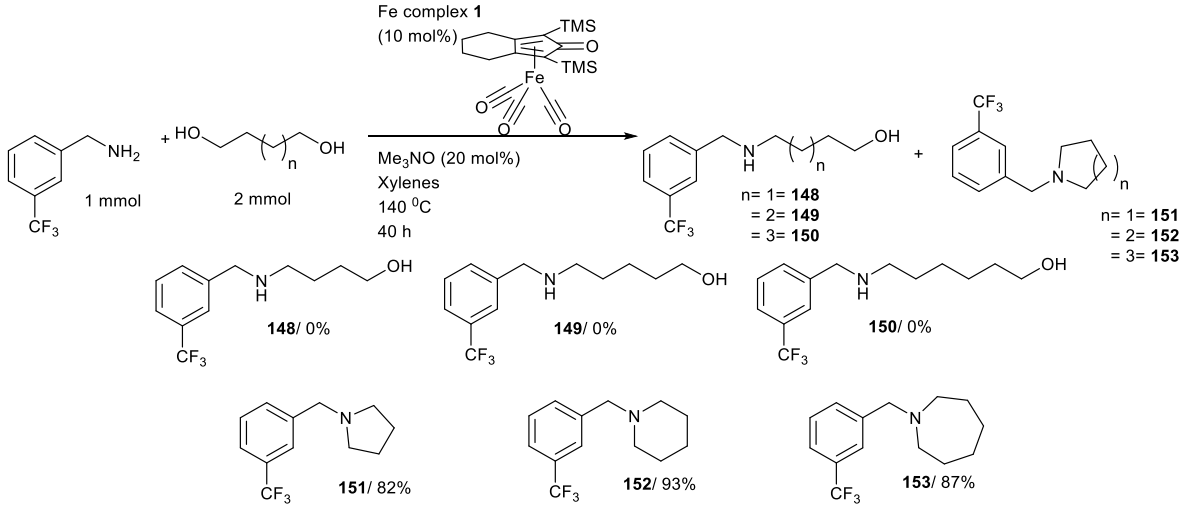
With the lower conversions/yields obtained with the reaction of diols with aniline, the work on the application of diols to the 'hydrogen borrowing' methodology was put on hold until success with the use of more basic amines, 4-phenylpiperidine and

3-trifluoromethyl)benzylamine, could be achieved . The use of 4-phenylpiperidine and a diol to produce a tertiary amine **147** with a primary alcohol functional group was then selected for testing (Scheme 75). However, this reaction failed to work with no clear reason for the failure of the reaction and work on this type of product was concluded.



Scheme 75: Failed Use of a Diol With 4-Phenylpiperidine

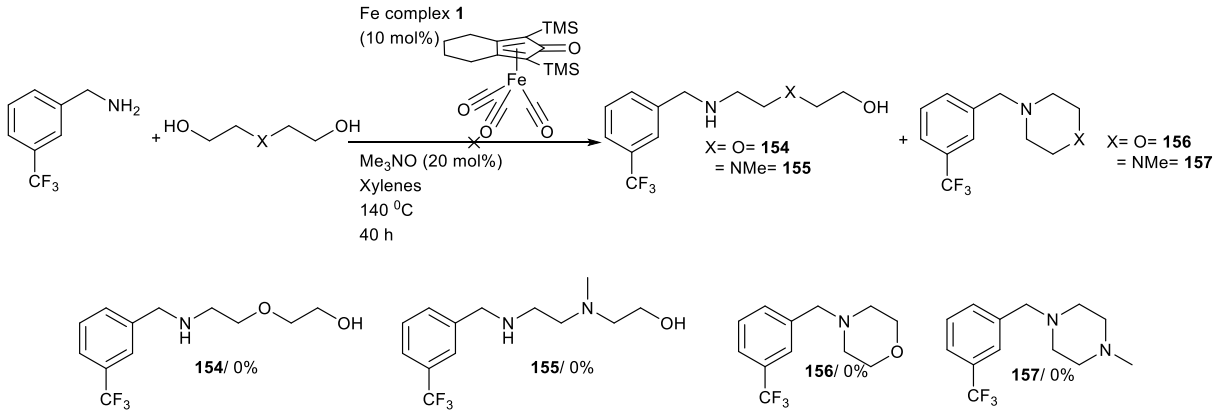
3-(Trifluoromethyl)benzylamine was then selected for testing in the 'hydrogen borrowing' methodology (Scheme 76) with diols due to past observations revealing that the amine possessed high reactivity towards a range of alcohols. This included primary aliphatic alcohols and secondary aliphatic alcohols. Benzylamine was not selected for use with diols due to its significantly poorer reactivity with primary aliphatic alcohols and with the previously observed reaction rates.



Scheme 76: Use of Dialcohols For 'Hydrogen Borrowing' Reactions

As with earlier testing, test reactions involving 3-(trifluoromethyl)benzylamine used the primary alcohols; 1,4-butanediol, 1,5-pentanediol and 1,6-hexanediol. In all three cases, the reactions were found to have completed with no trace of the amino alcohol intermediates **148**-**150** after the reaction time of 40 hours had completed. Full consumption of the 3-(trifluoromethyl)benzylamine starting reagent and only excess amounts of the dialcohol starting reagent remaining, alongside the desired tertiary amine products **151**-**153**, was observed.

With the improvement to the performance and conversion with the use of diols for 'hydrogen borrowing' methodology through the use of the more basic amine, 3-(trifluoromethyl)benzylamine, attempts were then made to extend the reaction scope to diols comprising other heteroatoms, using diethylene glycol and *N*-methyldiethanolamine (Scheme 77), to give a morpholine or piperazine ring, respectively.

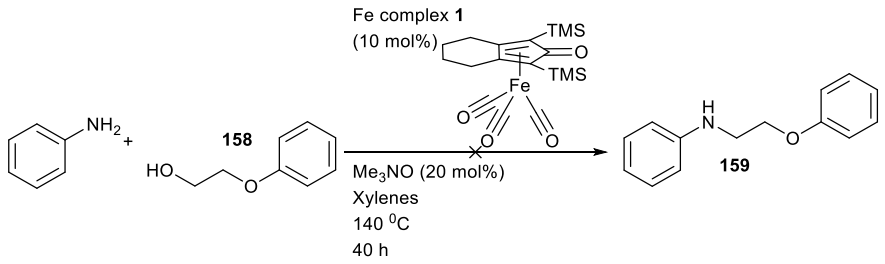


Scheme 77: Further Attempts With the use of Functionalised Dialcohols

However, both reactions failed to work, with no conversion to either the amino alcohol intermediates **154** and **155**, or the cyclic tertiary amines **156** and **157**. These results suggest the presence of a heteroatom in the dialcohol reagent causes interference in the catalytic pathway, possibly by blocking the empty valency of the activated iron complex and preventing the formation of the iron-hydride form of the iron complex. This hypothesis is supported by the results of the crude data analysis carried out on each reaction, with no observation of any mass

spectrometry or NMR peaks corresponding to any produced aldehyde, imine, amino alcohol intermediate or final tertiary amine products. Only starting reagents were observed.

These results also complement an earlier result from an attempt to incorporate an additional heteroatom into a product of the 'hydrogen borrowing' methodology, using aniline and 2-phenoxyethanol **158** (Scheme 78) to give the amine **159**. Crude reaction analysis showed no trace of any aldehyde, imine or amine products, with only the starting reagents observed.

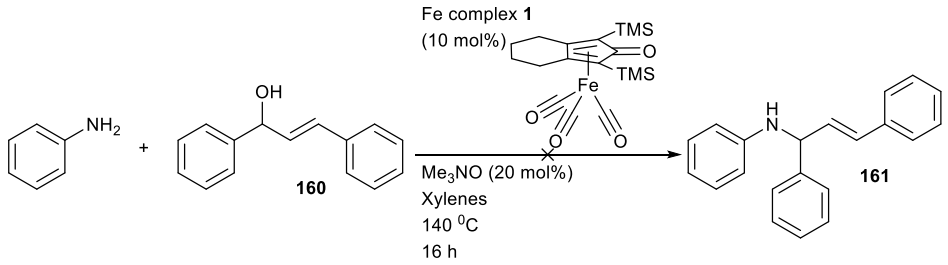


Scheme 78: Failed Use of 2-Phenoxyethanol

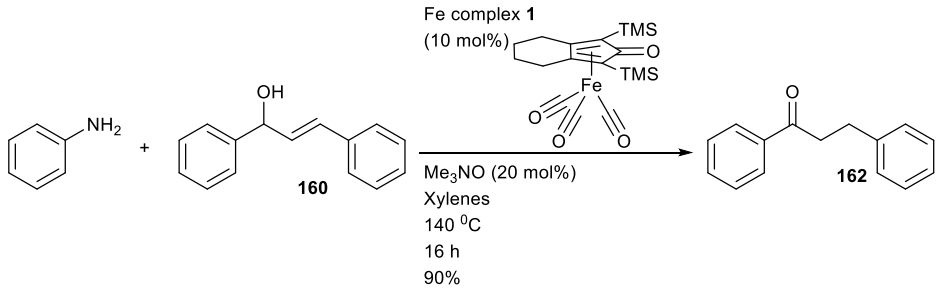
This result further supports the hypothesis of the presence of the heteroatom blocking the catalytic pathway and preventing any reactions from taking place.

(2.9) Amine Free Intramolecular 'Hydrogen Borrowing' of Alcohols

During the research into the incorporation of alkene and alkyne functional groups, the use of an alcohol containing a substituted alkene functional group was attempted with the use of 1 mmol of 1,3-diphenyl-2-propen-1-ol **160** and a 1 mmol excess of aniline (Scheme 79) with the intention of producing the amine **161**. Crude reaction analysis revealed no alteration to the aniline present with no remaining 1,3-diphenyl-2-propen-1-ol. NMR analysis revealed the presence of a pair of triplets, along with signals consistent with the presence of phenyl rings. The subsequent isolation of the unknown product compound and full data analysis with NMR, mass spec and IR spectrometry, revealed the unknown compound to be **162**, 1,3-diphenylprop-1-one, isolated with a yield of 90% (Scheme 80).



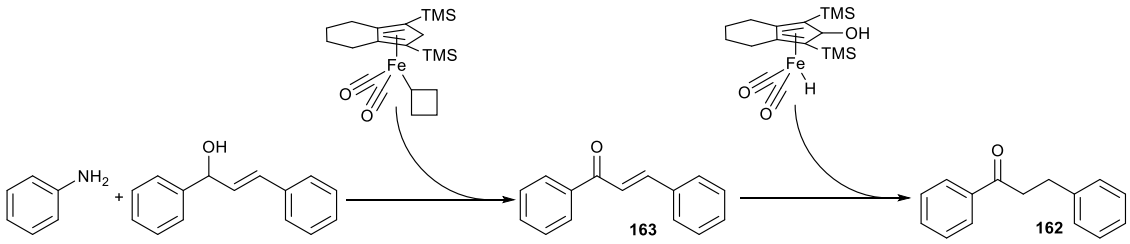
Scheme 79: Failed 'Hydrogen Borrowing' Attempt



Scheme 80: Example of a Rearrangement Reaction

This result revealed that the catalytic oxidation step was going forward to convert the hydroxy group to a carbonyl group and for such a high conversion, a reduction step of a reaction intermediate was clearly occurring to remove the hydrogen pair

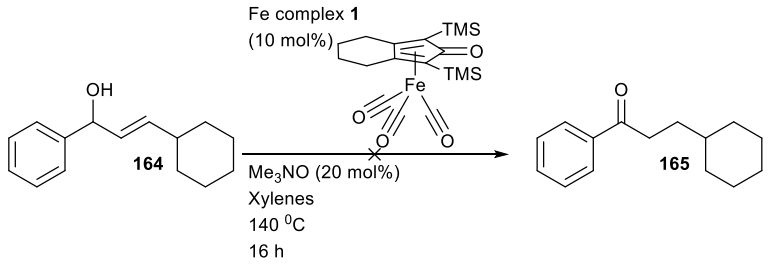
from the iron-hydride form of the iron complex, to allow the catalytic cycle to continue recurring. The absence of any alkene related signals in the ^{1}H NMR spectrum and the presence of a pair of triplet signals, each with an integration value of 2 and a deshielded position of ~3 ppm, with COSY NMR analysis showing coupling only between the two triplet signals, revealed that the reduction of the alkene functional group was occurring to give ketone **162**.



Scheme 81. Reaction Mechanism for Rearrangement Reaction

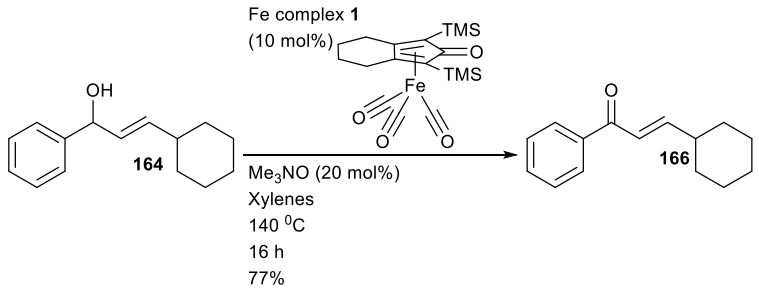
As aniline was present during this reaction pathway and no imine or amine products were observed during the crude reaction analysis, the production of ketone **162** suggests the reduction of the alkene functional group by the iron-hydride complex was far more favourable than the imine formation reaction between aniline and the reaction intermediate **163** (Scheme 81).

Due to the use of iron catalysis, the use of NMR techniques to follow and investigate the reaction pathway was not an option due to paramagnetic interference. However, there were still further studies to be carried out to further understand the discovered reaction and the decision was taken to make alterations to the phenyl substituents. Initially, alcohol **164** was synthesised and used at a scale of 1 mmol in a reaction (Scheme 82) using the same reaction conditions as with previous research work.



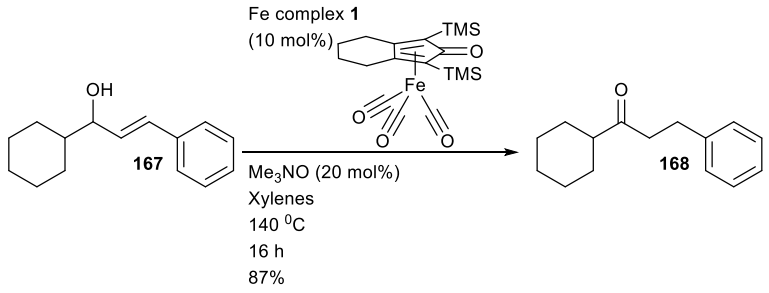
Scheme 82: Rearrangement of Ketone 164

However, ketone **165** was not isolated under the same conditions as used in Scheme 80, instead ketone **166** was isolated with a high yield of 77% (Scheme 83). This result presented a number of questions about the methodology being used, as ketone **166** was the proposed intermediate for the reaction and the reaction is made possible by a catalytic amount of the iron complex, there must have been an unobserved source of a hydrogen acceptor to allow the generation of the large yield of ketone **166**, as it is produced by the oxidation of alcohol **164** by the activated iron complex.



Scheme 83: Synthesis of Ketone 166

The failed reduction of the alkene group of the ketone **166** was also observed and this was hypothesised to have been caused by the absence of a phenyl ring being linked directly to the alkene group, thus removing the activation given to the alkene group for a reduction reaction to proceed. To further test this hypothesis, a second reaction was carried out on alcohol **167**, in which the phenyl and cyclohexyl ring positions have been reversed (Scheme 84).

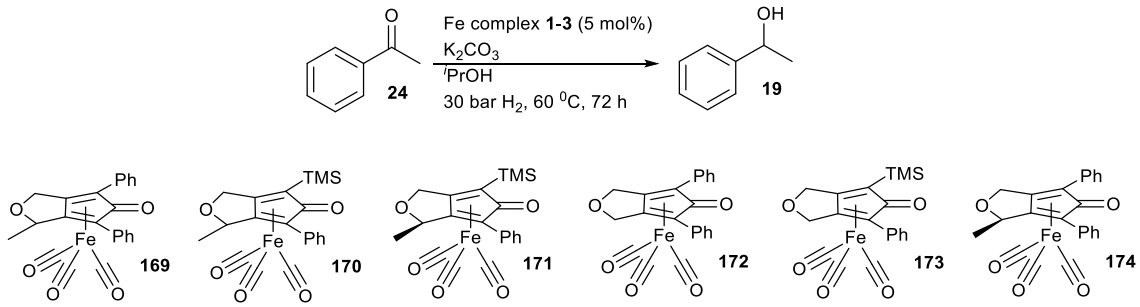


Scheme 84: Rearrangement of ketone 92

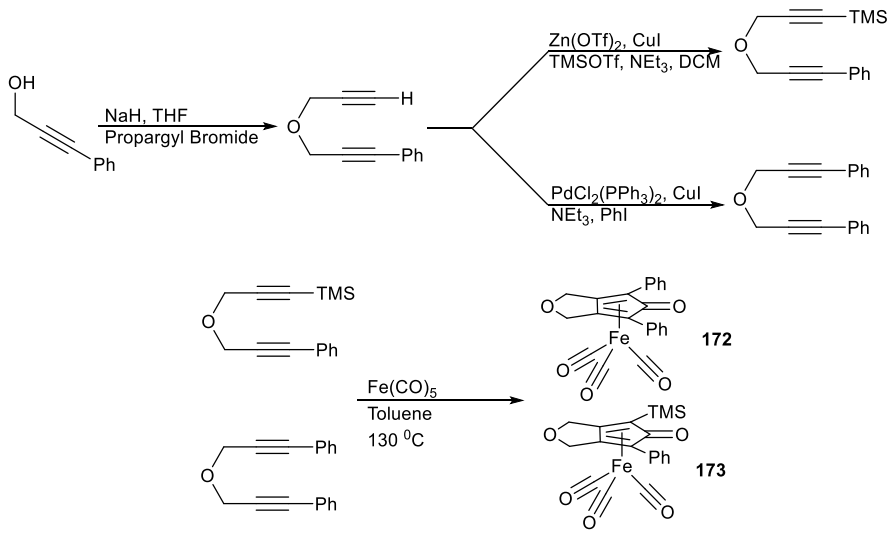
This reaction worked with full conversion to ketone **168** with full oxidation of the alcohol group and reduction of the alkene functional group, respectively. This result supported the hypothesis of the presence of a phenyl ring bonded to the alkene group was of the highest importance in activating the alkene group and allowing the reduction step to proceed. The types of groups present at the position adjacent to the hydroxy group were clearly of much lower significance, as the full 'hydrogen borrowing' pathway proceeded during the use of alcohols **160** and **167**.

(2.10) Investigation into the Synthesis of Asymmetric Iron Complexes

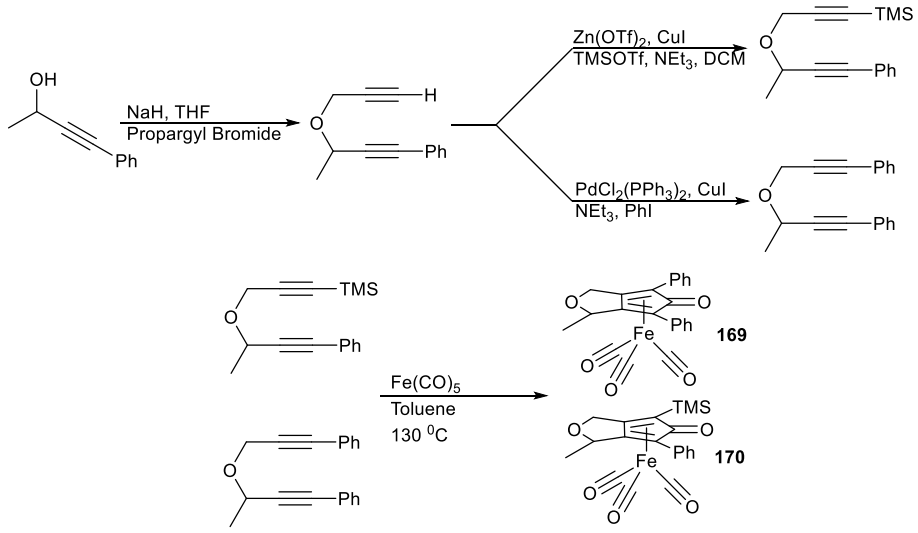
The development of an asymmetric cyclopentadienone iron complex was also investigated as part of the overall PhD project with a view to developing iron complexes to be used in pressure hydrogenation reaction (Scheme 85). To ensure the suitability of chiral cyclopentadienone iron complexes for use in pressure hydrogenation reactions, iron complexes **169**-**174** which had previously been synthesised and used in asymmetric transfer hydrogenation reactions by the Wills' group,[24] were tested under reaction conditions indicated in Scheme 85. Iron complexes **171**and **174** were synthesised in each case as two enantiomerically-pure diastereomers whereas complexes **169** and **170** were synthesised from a racemic starting material. Details of synthetic routes to iron complexes **169**-**174** is displayed in Schemes 86 & 87. For the synthesis of iron complexes **170** & **174**, the same synthetic approach as outlined in Scheme 87 can be used, except beginning with an enantiomerically enriched form of the starting alcohol reagent.



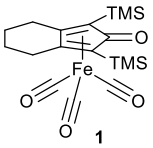
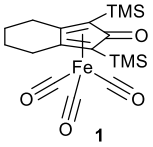
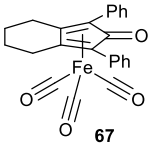
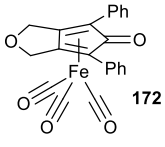
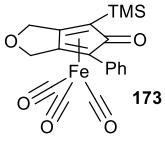
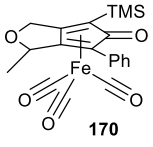
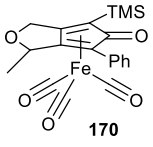
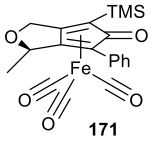
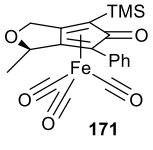
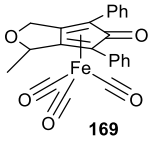
Scheme 85: Pressure Hydrogenation Catalysts



Scheme 86: Synthesis of Iron complexes 172-173



Scheme 87: Synthesis of Iron Complexes 169-171 & 174

Catalyst	Conditions	Result (two yields indicate a duplicate run)
 1	100 °C, 30 bar H_2, 72 h	66% & 99%
 1	60 °C, 30 bar H_2, 72 h	99% & 97%
 67	60 °C, 30 bar H_2, 72 h	80% (repeated twice)
 172	60 °C, 30 bar H_2, 24 h	18% & 21%
 173	60 °C, 30 bar H_2, 24 h	19% & 13%
 170 Isomer 1	60 °C, 30 bar H_2, 72 h	34% & 33%
 170 Isomer 2	60 °C, 30 bar H_2, 72 h	24% & 29%
 171	60 °C, 30 bar H_2, 72 h	6% & 6%
 171	60 °C, 30 bar H_2, 72 h	5% & 5%
 169	60 °C, 30 bar H_2, 72 h	8% & 12%

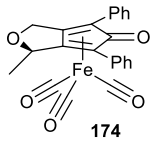
 174	60 °C, 30 bar H_2, 72 h	1% & 2%

Table 4: Hydrogenation of Acetophenone Using Iron Catalysts

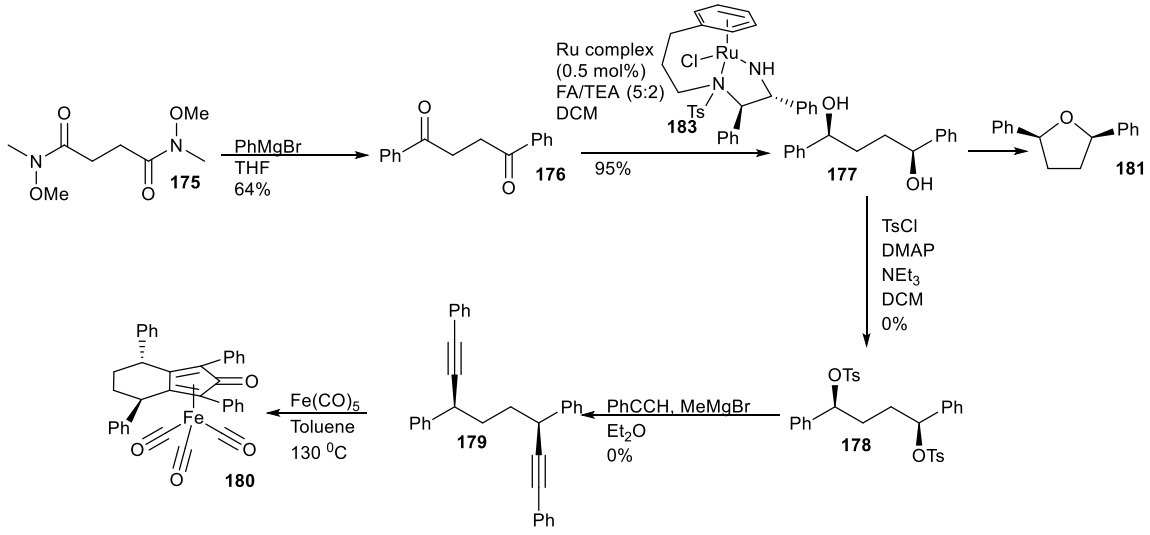
The testing of both racemic diastereomers of complexes **169** and **170** in the hydrogenation of acetophenone (Table 4) gave products in low conversions of 24-34% and 8-12%, respectively. Although these results were poor, testing continued onto the enantiopure diastereomers of iron complex **171**, which gave products in very low conversions of 5-6%. These results were complemented by the testing of the asymmetric diastereomers of iron complex **174** (Table 4), giving conversions of up to 2%. Since low conversions had also been observed with the earlier testing of iron complexes **172** and **173**, the hypothesis was deduced that the ether functional group connected to the cyclopentadienone ring may be unstable and cause the iron complex to decompose under pressure hydrogenation conditions. This hypothesis was supported through the observation of the reaction solutions becoming suspensions. To provide further evidence to support this conclusion, two subsequent test reactions were carried out using iron complexes **1** and **67** (Scheme 85). There is no ether functional group in iron complexes **1** and **67**, and the use of such complexes as hydrogenation catalysts under the reaction conditions used in Scheme 85 gave homogeneous reaction solutions with no observed decomposition of the activated iron complexes and conversions of 80% and 99% to the alcohol, respectively.

These results demonstrated that although cyclopentadienone iron tricarbonyl complexes containing an aliphatic ring connected to the cyclopentadienone ring were applicable for pressure hydrogenation methodology, the use ether-containing complexes is not an option due to decomposition issues giving poor conversion results.

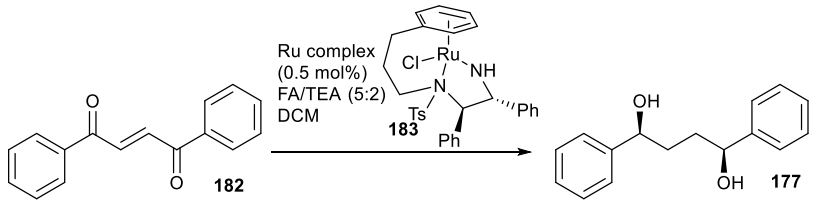
By incorporating these observations into the development of the new iron complexes, a new synthetic strategy was devised to synthesise the asymmetric

complex **180** via compounds **175**-**179** (Scheme 88). The synthesis of **175** was completed in good yield and conversion, however each attempt to use the diWeinweb reagent in an addition reaction with various equivalents of phenylmagnesium bromide met with low reaction conversions and purification issues.

Due to the severe purification issues and high levels of contamination in the isolated product material, which was causing purification issues with the next reaction step, the synthesis of **176** was halted and diol **177** was instead synthesised directly via an alternative route from diketone **182** using an asymmetric transfer hydrogenation reaction (Scheme 89).



Scheme 88: Proposed Synthetic Route

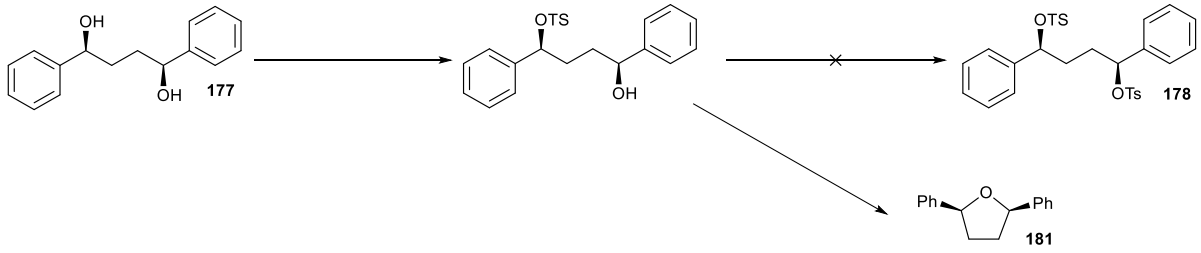


Scheme 89: Reduction of Diketone 182

The reasoning behind the change to the synthetic pathway was that with the difficulties surrounding the synthesis of diketone **176** giving poor yields with considerable contamination and the high cost of purchasing diketone **176** meant a change to the synthetic strategy was needed, as a major purpose of iron catalysis is their potential high cost effectiveness.

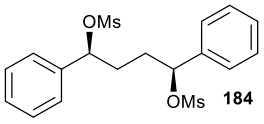
Although the use of tethered ruthenium catalysts, such as **183** for the reduction of carbonyl and, to some extent, alkene groups was known through previous work completed by the Wills' group, this type of catalysis had not been applied to the reduction of a diketone of a structure analogous to ketone **182**. There was a possibility of the reaction giving significantly different ee values for the reduction of each carbonyl group and giving a poor de value for the production of the dialcohol **177**. However, the reduction process worked well with the product formed with a de value of 60% (refer to next section) and the next reaction in Scheme 86 was attempted; the synthesis of a ditosylate 178.

The synthesis of disolyate **178** proved to be challenging, as the reaction followed an unintended pathway, giving a furan derivative 181 (Scheme 90) and no other products. This result can be explained by the hypothesis that the reaction to form ditosylate **178** would occur via the formation of the first and second tosylate groups in sequence. Hence the formation of the first tosylate group would be followed by a faster formation of furan **181** via the intramolecular substitution of a OTs group to allow a more favourable ring formation reaction to occur (Scheme **88**).

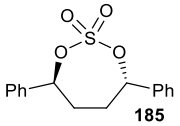


Scheme 90: Proposed Reaction Pathway OTs not OTS

This problem could not be overcome and the decision was taken to change the direction of the synthetic strategy again to look at the possible use of either dimesylate **184** or compound **185** as possible alternatives.



184



185

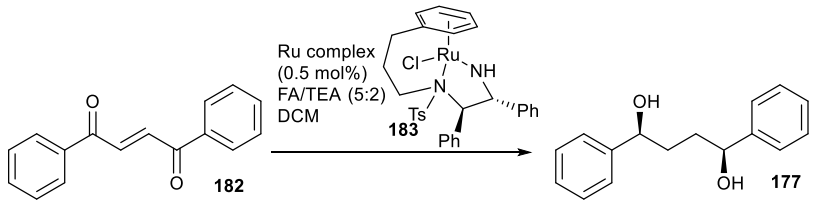
However, difficulties were observed with the synthesis of both **17** and **18**, with compound **18** not being synthesised at all. In the case of the synthesis of dimesylate **17**, material was synthesised which was considered to have the correct spectrometric characteristics to be the correct compound, but when the isolated material was used in the next reaction step to synthesise compound **13**, the reaction failed.

A possible reason behind the reaction difficulties with the use of the dimesylate material were hypothesised to possibly be caused by decomposition issues with the storage of the isolated material. Another cause for the failed reaction could be an unobserved conflicting reaction producing an alternative reaction pathway and producing no desired compound.

As the work on an asymmetric cyclopentadienone iron tricarbonyl complex was not a major component of this project and designed to hopefully tie into future work on 'hydrogen borrowing' chemistry, the decision was then taken to terminate work on the development of an asymmetric iron complex, due to the lack of positive progress and the time restraints of the PhD project.

(2.11) Investigations into the Novel Application of Ruthenium Catalysts

During the work on the development of an asymmetric iron complex, a new application of the ruthenium catalyst **183** being used had been observed (Scheme 91) and further investigation into the reaction pathway was undertaken.

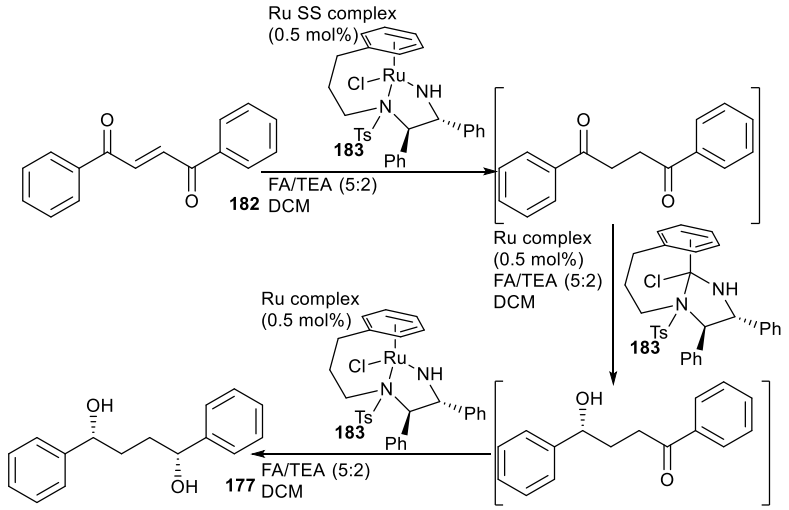


Scheme 91: Reduction of Diketone 182

As diketone **182** possesses three groups for reduction; one alkene group and two carbonyl groups, a successful reduction process was hypothesised to follow one of two different pathways. The first case would begin with the reduction of one of the carbonyl groups, followed by the alkene group and finishing with the second carbonyl group. However, this reaction pathway would cause each carbonyl group reduction to occur in a different environment, resulting in different ee values and a poorer overall de value for the reduction reaction. The second hypothesised reaction pathway was the preferential reduction of the alkene group occurring and completing initially before the reduction of the carbonyl groups would begin. This would produce a symmetrical unsaturated diketone and allow the reduction of each carbonyl group to occur within a slightly different chemical environment and theoretically give similar e.e. values, producing a higher d.e. value.

To investigate and gain further information to deduce the reaction pathway of this reduction process, the reaction was followed by ^{1}H NMR spectrometry over a 24 hour period. The results of the experiment supported the reaction following the second pathway mentioned above, with the preferential reduction of the alkene group in the unsaturated diketone **182** occurring over a time period of two hours, giving the saturated diketone **178** as an intermediate in the reduction. The reduction of the first carbonyl group began only when the majority of the

unsaturated diketone had been converted to **178**, with the final reduction of the second carbonyl group taking place almost simultaneously with the other carbonyl reduction reaction and giving an ongoing reaction mixture of both a mono-alcohol and a dialcohol. This was caused by the carbonyl reduction steps being much slower than the C=C reduction. The presence of each alcohol product could be observed through the different chemical shift values for the C**H**OH groups in the mono and dialcohol compounds. These two final reaction steps were completed within a 24 hour period with full conversion to the dialcohol compound (Scheme 92).



Scheme 92: Reduction Reaction Pathway

In order to confirm the reaction pathway for the reduction of diketone **182**, the reaction was followed by ^{1}H NMR analysis. Figure 7 displays the reduction reaction after 30 minutes; the peak corresponding to the alkene group at ~8 ppm is being reduced and a peak at ~3 ppm begins to appear, which corresponds to the diketone intermediate displayed in Scheme 92.

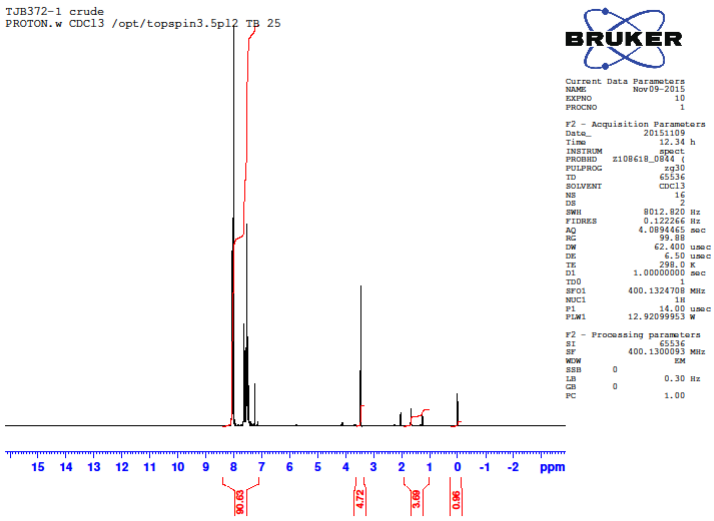


Figure 7: Initial ^{1}H NMR Spectrum of Reduction Reaction

After 3 hours had passed, the NMR spectrum obtained (Figure 8) revealed that all the alkene group-containing diketone had been converted.

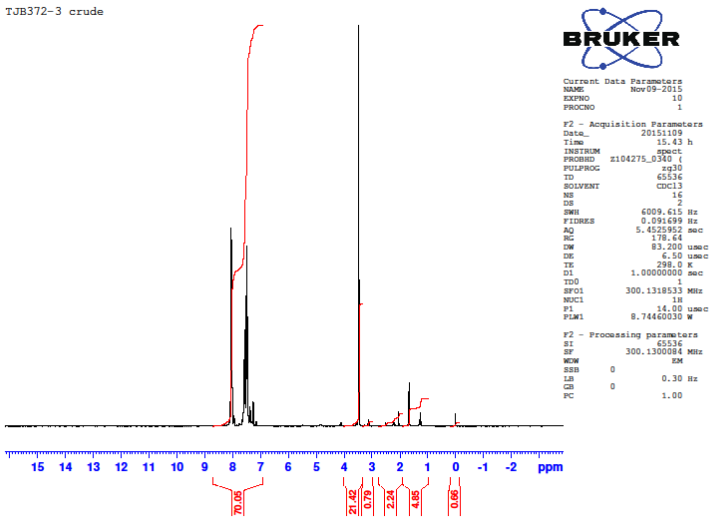


Figure 8: Second ^{1}H NMR Spectrum of Reduction Reaction

The reaction was then further monitored every 2 hours for another 8 hours and the gradual reduction of the carbonyl groups was observed, sequentially producing

both the mono-alcohol intermediate and the final reduction product **177**. This was observed through the presence of ^{1}H NMR peaks corresponding to the C*H*OH groups of the mono-alcohol and the dialcohol **177** products at ~5 ppm in Figure 9.

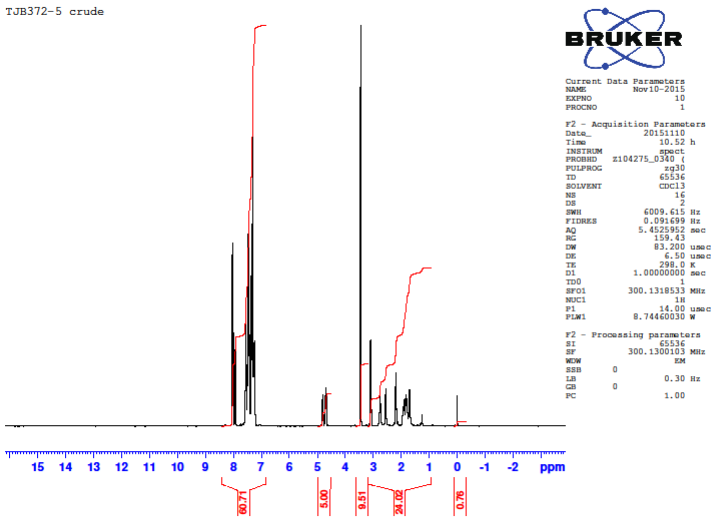


Figure 9: Third ^{1}H NMR Spectrum of Reduction Reaction

This reduction had completed by the following, when a subsequent NMR sample revealed full conversion to the dialcohol **177** with no remaining starting reagent or intermediates. The ^{1}H NMR data obtained from this study, shown in Table 5 and Figure 10, reveals the reaction process and reveals that although the reduction of the alkene is a fast process, the reduction of the carbonyl groups is a much slower process.

Time/ h	Starting Material **182**/ %	Saturated Diketone/ %	Mono-Alcohol/ %	Dialcohol **177** / %
0	100	0	0	0
0.5	83	17	0	0
1	44.2	54	1.8	0
2	0	96.2	3.8	0
4	0	74.6	20.9	4.5
6	0	40.0	35.2	24.8
24	0	0	0	100

Table 5: Reduction Reaction Results

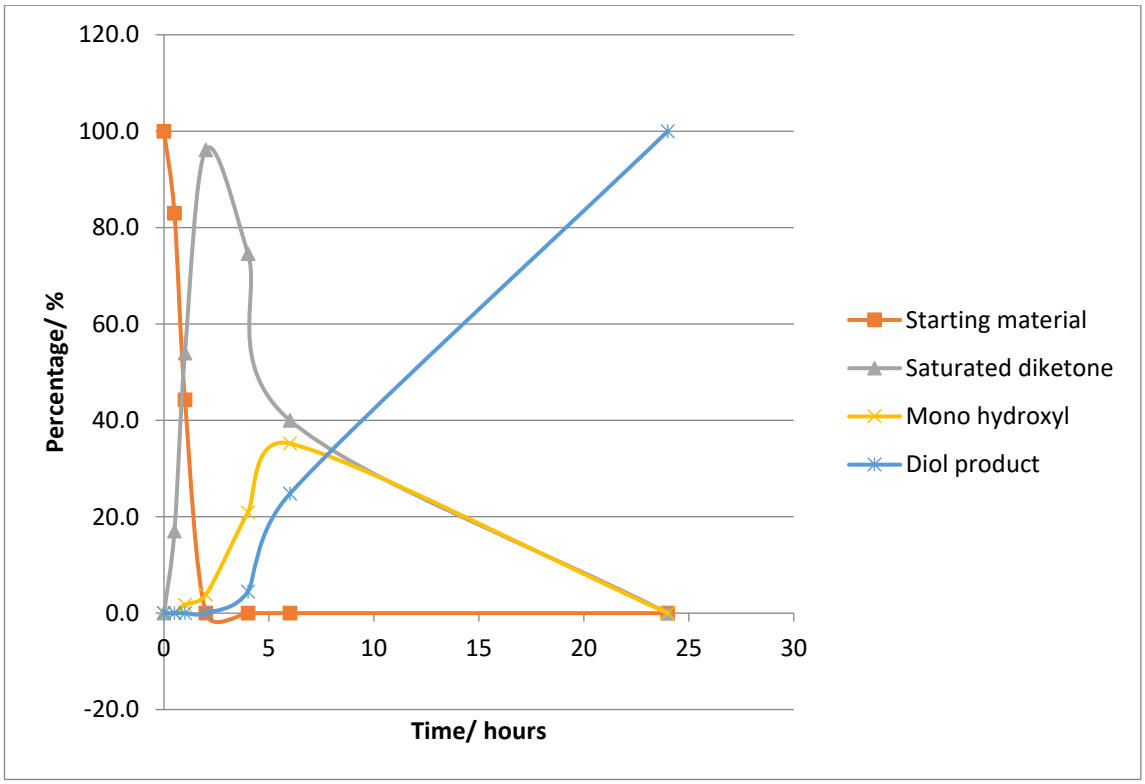
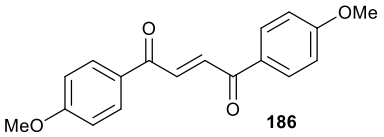


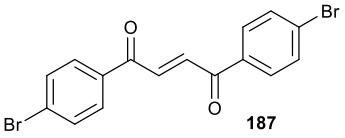
Figure 10: Graphical Output For The Time Course of Reduction Reaction

At this point, work was then undertaken to investigate the effect of changing the substituents on the aromatic rings of the unsaturated diketone on the reaction rate

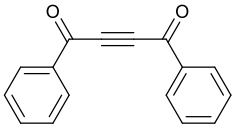
of the reduction reaction and three reduction targets were identified; (*E*)-1,4-bis(4-methoxyphenyl)but-2-ene-1,4-dione **186**, (*E*)-1,4-bis(4-bromophenyl)but-2-ene-1,4-dione **187** and 1,4-diphenylbut-2-yne-1,4-dione **188**.



186

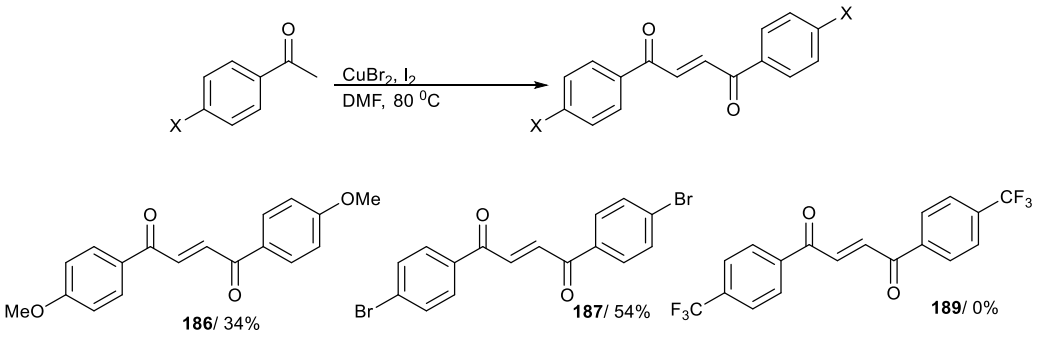


187



188

The methoxy and bromo-substituted diketones **186** and **187** were both synthesised through a methodology derived from a published procedure for the synthesis of unsaturated diketones (Scheme 93).[39] There were no more attempts made on other examples of such unsaturated diketones, as the synthetic procedure being used was found to be limited to specific examples and expanding the scope to other diketone derivatives was difficult. As the synthesis of diketone **187** was low yielding and no de could be obtained for the following reduction reaction, the synthesis of diketone **189** was attempted to obtain another example of a compound containing electron-withdrawing group however this synthetic attempt failed with no conversion to the diketone **189**. With the time restraints within the PhD project and no other clear means of synthesising this type of unsaturated symmetrical diketones, the synthesis of this type of diketone was halted and the work on the application of ruthenium catalysis to the reduction of this type of diketones was also halted after completing work on compounds **186**, **187** and **189**.

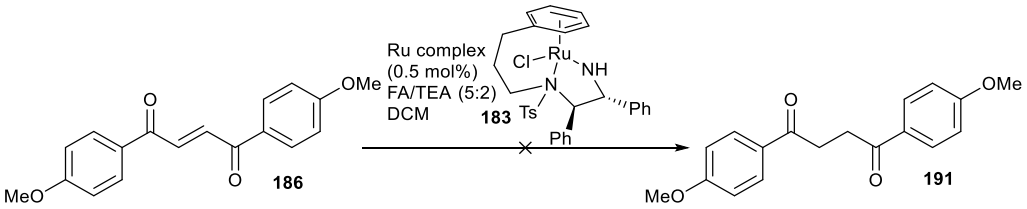


186/ 34% **187**/ 54% **189**/ 0%

Scheme 93: Synthesis of Unsaturated Diketones

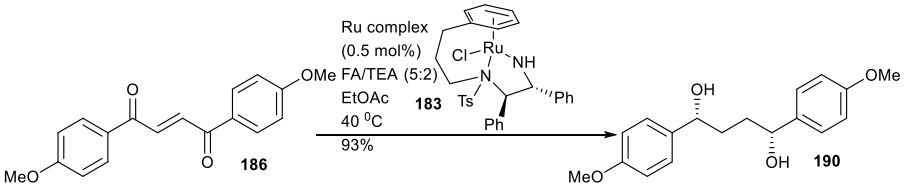
The reduction of diketone **186** was found to be difficult and no subsequent conversion to the dialcohol **190** using the conditions displayed in Scheme 89 was

observed. This failed reaction attempt was hypothesised to have been caused by solubility issues associated with the first reduction product, the saturated ketone. The reaction halted with the precipitation of a solid in the reaction solution and the working up of the reaction revealed only the presence of the saturated ketone **191** (Scheme 94). Repeating the reaction with the same set of conditions gave only the same result, irrespective of the reaction time used, increasing the reaction made no difference to the outcome of the reaction.



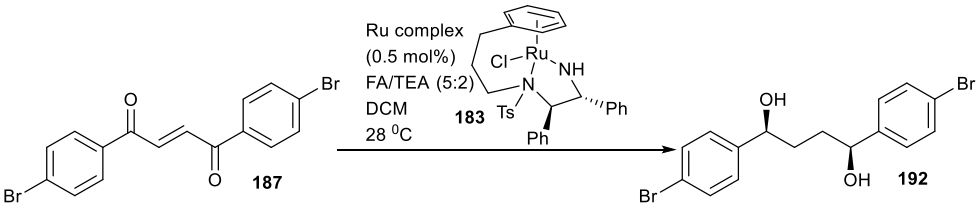
Scheme 94: Unsuccessful Reduction Attempt of Diketone 186

In order to get the reaction to work, the reaction temperature was increased to 40 ^{0}C and the reaction solvent was changed from dichloromethane to ethyl acetate. These changes prevented the precipitation of the reaction intermediate and allowed the reduction reactions to proceed to the second and third reductions of the carbonyl functional groups. However, the reaction pathway proceeded at a much slower rate and required a reaction time of 72 hours for completion (Scheme 95). This observation is consistent with previous observations that have been made concerning the slower reduction of methoxy substituted acetophenone derivatives.[40] However, due to complications with the chiral HPLC analysis and the inability to identify the *meso* peaks in the obtained F^{19} NMR spectra from the Mosher's acid derivatisation, meant no d.e. values were obtained.



Scheme 95: Reduction of Methoxy Substituted Diketone 186

The reduction of diketone **187** was attempted in order to assess the effect of incorporating electron withdrawing groups into the diketone starting material on the rate of the reduction reaction and this was carried out successfully using the same conditions as used with the reduction of 1,4-diphenylbut-2-ene-1,4-dione **182** (Scheme 96) without having to use a higher temperature of 40 ^{0}C and ethyl acetate.



Scheme 96: Reduction of a Bromo-substituted Diketone

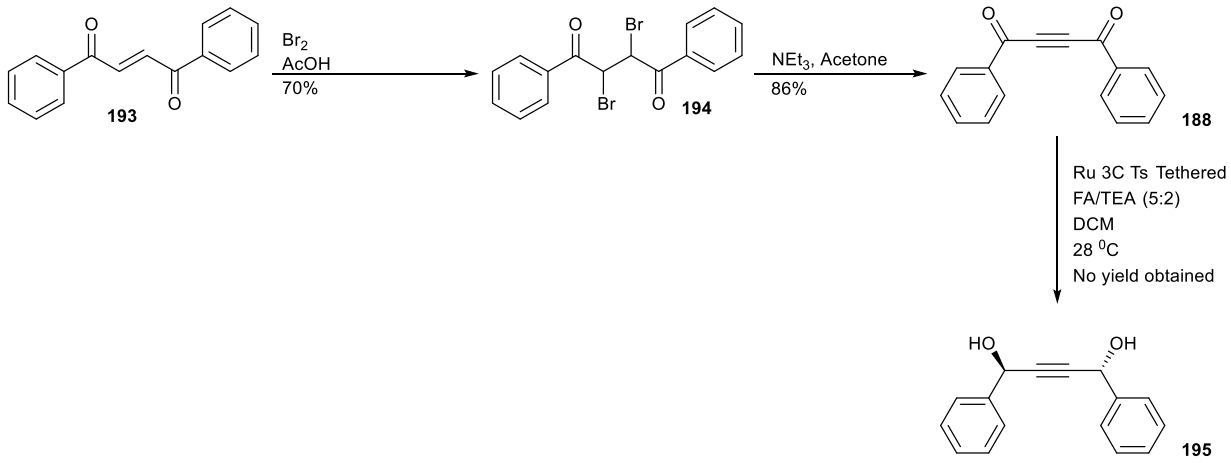
The reaction was completed overnight with complete conversion from the diketone **187** to the dialcohol **192**. However, the crude reaction mixture contained too many impurities to allow the determination of the d.e. via Mosher's Acid derivatisation to be carried and give a clear output of the reaction d.e. by ^{19}F NMR calculation. The use of chiral HPLC was also explored, but was found to not be possible, due to the failure in attempting to resolve the corresponding peaks for the *RR*, *meso* and *SS* products. The work did confirm the successful application of this type of ruthenium catalyst to the reduction of another example of a substituted symmetrical unsaturated diketone, but no de was obtained. As the isolation of all material related to the dialcohol **192** had been achieved by column chromatography, the possible use of recrystallisation would have posed a considerable risk of producing an incorrect representation of the reaction outcome with regards to de by enriching one diastereomer relatively against another. Hence the determination of de could not be carried out accurately after any purification work had taken place.

A significant issue with the project was the synthesis of the diketone substrates, as the reaction displayed in Scheme 93 was not capable of reliably delivering diketones **186** and **187**, with the isolated yields of each compound varying significantly in each reaction attempt and a large time input being required in order to isolate each diketone from a complex reaction mixture through column

chromatography. Another significant drawback of the dialcohols produced through the reduction of diketones **182**, **186** and **187** was the difficulties concerned with the running of crude samples through HPLC analysis to determine the de values. A significant number of HPLC columns and sets of conditions were tested, but the separation of the *RR*, *SS* and *meso* peaks could not be accomplished and all de determination had to be carried out through Mosher's Acid derivatisation and ^{19}F NMR analysis. With the reduction of diketone **182**, the obtained d.e. values for the *RR* reduction was 50% and for the *SS* reduction, 50%. For the reduction of the *p*-methoxy diketone derivative **186**, no d.e. could be obtained with the use of either the *RR* or the *SS* Ru (II) catalysts, through the means of chiral HPLC or via Mosher's Acid derivatisation/F^{19} NMR analysis. In the case of Mosher's Acid derivatisation, the obtained F^{19} NMR spectra generated insufficient information to identify the peaks generated by the *meso* diastereomers. Hence, no calculation of the d.e. could be obtained. However, NMR data obtained suggested higher d.e. values than those obtained from the *RR* and *SS* reductions of diketone **186**.

A final piece of research for this project was on an alternative substrate **188**. This diketone possesses an alkyne group instead of an alkene group and the goal of this piece of work was to observe the reactivity of the alkyne and carbonyl groups towards a reduction reaction catalysed by the same ruthenium catalysis used previously. Diketone **188** was successfully synthesised through the strategy displayed in Scheme 97[41] from diketones **193** and **194**, with yields of 70% and 87%, respectively.

The reduction of diketone **188** was successfully completed overnight under the conditions displayed in Scheme 96 to give dialcohol **195**. However, no d.e. was determined for this reaction as there was a large amount of contamination in the crude material obtained from the reduction reaction, which caused issues with the potential use of using Mosher's Acid derivatisation to provide the de value for the reaction and HPLC analysis was not possible due to impurities, which could not be removed.



Scheme 97: Synthesis and Reduction of Diketone 188

(2.12) Conclusions and Potential Future Work

In conclusion, a series of novel iron complexes were initially synthesised and were subsequently used in a study into the effect of altering the carbon chain length in the alcohol reagent and the electronic environment of the iron catalyst used in a 'hydrogen borrowing' reaction using aniline as the amine reagent. However, the results of this study revealed no overall trends in the obtained conversion values and the developed methodology was utilised to produce a range of aniline-based secondary amines in high yields of 88-95%, synthesised from secondary aliphatic alcohols. The final part of this area of study concerned the use of the 'hydrogen borrowing' methodology to synthesise aniline-based tertiary amines using aliphatic dialcohols (e.g. cyclohexanol). However, this area of work only generated yields of up to 42%.

With an alternative set of reaction conditions, the 'hydrogen borrowing' methodology was then applied to the synthesis a range of secondary and tertiary amines from more basic amine reagents (e.g. piperidine, benzylamine, diallylamine or *N*-methylcyclohexylamine), which had been a challenging area of chemistry to use. With this methodology established, the use of aliphatic dialcohols was then revisited to synthesise tertiary cyclic amines was then revisited and a range of benzylamine derivatives were synthesised with excellent yields of 87-92%.

Efforts were also made to incorporate additional functionality into the product amines and a large range of amines, both aniline-based and more basic amine targets, containing terminal alkene or TMS-alkynyl groups were synthesised, thus giving a novel means by which to synthesise such targets.

The development of a novel asymmetric (cyclopentadienone)iron tricarbonyl complex was also explored, but this area of work was found to be particularly challenging and due to the time restraints of the PhD project, work on this are of the project was halted.

However, the attempted development of a novel asymmetric iron complex revealed a novel application of the Ru(II)/TsDPEN hydrogen transfer catalysts with the total

reduction of symmetrical unsaturated diketones to give the symmetrical saturated dialcohol products.

(2.13) Future Work

Potential areas of interest for work on (cyclopentadienone)iron tricarbonyl complexes and the subsequent application of 'hydrogen borrowing' methodologies, would be the development of asymmetric iron complex and applying these complexes to 'hydrogen borrowing' reaction involving unsymmetrical secondary alcohols. This would potentially allow the selective production of a specific enantiomer of an amine product through the 'hydrogen borrowing' process.

Other avenues of possible work could be to assess the application of (cyclopentadienone)iron tricarbonyl complexes to 'hydrogen borrowing' reactions using other nitrogen-containing reagents (e.g. amides).

Experimental

(3.1) General Procedures

General Experimental Methods

All solvents and reagents for the synthesis of iron complexes and catalytic reactions were degassed before use and all reactions were carried out under either a nitrogen atmosphere. Reactions were monitored by TLC using aluminium backed silica gel 60 (F254) plates, visualized using UV 254 nm and phosphomolybdic acid or potassium permanganate dips as appropriate. Flash column chromatography was carried out routinely on silica gel. Reagents were used as received from commercial sources unless otherwise stated. Dry solvents were purchased and used as received. All synthesis of iron complexes and iron catalytic reaction were carried out in ACE 15 Ml 150 psi pressure tested pressure tubes and heated in aluminium heating blocks. 1H NMR spectra were recorded on a Bruker DPX (400 or 500 MHz) spectrometer. Chemical shifts are reported in δ units, parts per million relative to the singlet at 7.26 ppm for chloroform and 0.00 ppm for TMS. Mass spectra for analysis of synthetic products were recorded on a Bruker Esquire2000 or a Bruker MicroTOF mass spectrometer. Coupling constants (J) are measured in Hertz. IR spectra were recorded on a Perkin-Elmer Spectrum One FT-IR Golden Gate. Melting points were recorded on a Stuart Scientific SMP 1 instrument and are uncorrected.

General Procedure for Aniline Related 'Hydrogen Borrowing' Reactions:

Iron(1,8-diphenylocta-1,7-diyne) tricarbonyl (43.0 mg, 0.100 mmol, 0.1 equivs.) was placed in a thoroughly dried 15 mL pressure tube with a stirrer bar and Xylene (0.5 mL) was added. Distilled aniline (137 µL, 139 mg, 1.5 equivs.) and alcohol (1.00 mmol, 1 equiv.) were added with stirring. Pressure tube was sealed with a septum and degassed through a nitrogen bubbler for 15 minutes. Trimethylamine N-oxide (7.00 mg, 0.09 mmol, 0.09 equivs.) was then added with stirring and the solution was further degassed for 5 minutes before being sealed with a pressure tube lid and stirred at 140 ^{o}C for 16 hours. Tubes were then allowed to cool to room

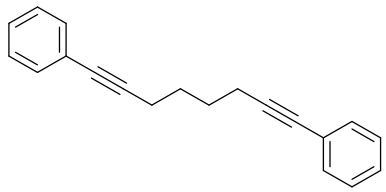
temperature and contents were passed through celite filtration with ethyl acetate. Solvent removal via a rotary evaporator gave a dark brown residue.

General procedure for Sonogashira Reactions:

In a dried and degassed 100 mL round-bottom flask, 1,7-octadiyne (1.00g, 9.42 mmol) and aryl iodide (20.7 mmol, 2.2 equivs.) were dissolved in anhydrous THF (34 mL) with stirring. $PdCl_2(PPh_3)_2$ (50.0 mg, 0.0712 mmol, 0.03 equivs.) and CuI (27.0 mg, 0.142 mmol, 0.06 equivs.) were added to the stirred solution to give a yellow suspension. $^{i}Pr_2NH$ (13.2 mL, 9.53 g, 10 equivs.) and a thick precipitate formed. Vigorous stirring overnight and celite filtration with ethyl acetate, to remove precipitate and metal impurities, gave a brown residue after solven removal via a rotary evaporator.

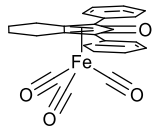
(3.2) Synthesis of Complex Precursors and Iron Complexes

1,8-Diphenylocta-1,7-diyne.



This compound is known and has been fully characterised.[42] 1,7-Octadiyne (1.00 g, 9.42 mmol) was added to a stirred solution of iodobenzene (4.23 g, 20.7 mmol) in dry THF (34 mL . $PdCl_2(PPh_3)_2$ (50.0 mg, 0.071 mmol), CuI (27.0 mg, 0.141 mmol) and $^{i}Pr_2NH$ (9.53 g, 94.2 mmol) were added and reaction was stirred at room temperature overnight. The reaction solidified and was therefore passed through a celite/silica plug with 20% ethyl acetate/ pentane to give a brown oil after solvent removal under reduced pressure. Recrystallisation from methanol gave the product as a white solid (2.19 g, 8.49 mmol, 90%). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.40 (4 H, d, *J*=4.0 Hz, Ar*H*) 7.27 (6H, d, *J*=4.0 Hz, Ar*H*) 2.48 (4H, br. s., $CH_2CH_2CH_2CH_2$) 1.79 (4H, br. s., $CH_2CH_2CH_2CH_2$) ppm.

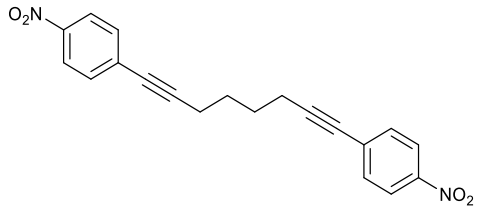
Iron(1,8-diphenylocta-1,7-diyne) tricarbonyl



This compound is known and has been fully characterised.[42] 1,8-Diphenylocta-1,7-diyne (0.500 g, 1.94 mmol) was placed in a dried pressure tube with a stirrer bar with dry toluene (5.00 mL), and $Fe(CO)_5$ (786 µL, 1.14 g, 5.82 mmol) was added. The reaction solution was degassed thoroughly with N_2 for 15 minutes. The tube was sealed and heated to 130 ^{o}C overnight. The tube was then allowed to cool to room temperature and tube contents were passed through a silica plug with 50:50 EtOAc: pentane. The solvent was then removed under reduced pressure to give the product as a brown solid (0.729g, 1.71 mmol, 88%). Mp 164-165 ^{o}C, lit. Mp 165-166 ^{o}C; ν_{max} 3062, 2950, 2864, 2052, 2002, 1981, 1641, 1627, 1500, 1439, 1336, 1217,

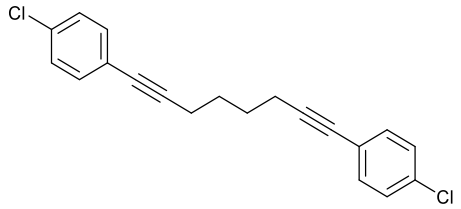
1187, 793, 760, 706, 694, 613, 598, 585, 569, 536, 494, 430 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.74 (4H, d, *J*=7.2 Hz, Ar*H*) 7.26 - 7.47 (6H, m, Ar*H*) 2.64 - 2.89 (4H, m, CH_2) 1.94 (4H, br. s, CH_2) ppm; ^{13}C NMR (126 MHz, $CDCl_3$) δ 22.30, 23.73, 81.92, 100.41, 127.94, 128.42, 129.69, 131.34, 169.47, 208.98 ppm; m/z (ESI) 427 $(M+H)^+$, 449 $(M+Na, 100\%)^+$.

1,8-Bis(4-nitrophenyl)octa-1,7-diyne.



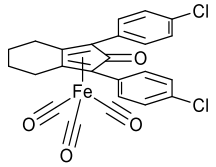
This compound is novel. 1,8-Bis(4-nitrophenyl)octa-1,7-diyne was synthesised in the same procedure as used previously for 1,8-diphenylocta-1,7-diyne using 1,7-octadiyne (300 mg, 2.83 mmol) and 1-iodo-4-nitrobenzene (1.551 g, 6.23 mmol), $PdCl_2(PPh_3)_2$ (50.0 mg, 0.0707 mmol), CuI (27.0 mg, 0.141 mmol) and $^{i}Pr_2NH$ (6.60 mL, 4.77 g, 47.1 mmol) to give 1,8-bis(4-nitrophenyl)octa-1,7-diyne as an orange solid (0.339 g, 0.974 mmol, 34%). Mp 40-42 ^{o}C; (ESI) Found 371.1001, $C_{20}H_{16}N_2NaO_4$ requires 371.1002; ν_{max} 2931, 1590, 1510, 1338, 1106, 852, 749, 715, 517, 468 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.16 (4 H, d, *J*=8.0 Hz, Ar*H*) 7.52 (4 H, d, *J*=8.0 Hz, Ar*H*) 2.54 (4 H, br. s., $CH_2CH_2CH_2CH_2$) 1.82 (4 H, br. s., $CH_2CH_2CH_2CH_2$) ppm; ^{13}C NMR (101 MHz, $CDCl_3$) δ 146.68, 132.29, 130.74, 123.54, 95.79, 79.75, 27.57, 19.19 ppm; m/z ESI 349 $(M+H, 100\%)^+$.

1,8-(4-Chlorophenyl)octa-1,7-diyne



This compound is novel. 1,8-(4-Chlorophenyl)octa-1,7-diyne was synthesised through the same method as for the synthesis of 1,8-diphenylocta-1,7-diyne using 1,7-octadiyne (0.300 g, 2.83 mmol) and 1-chloro-4-iodobenzene (1.49g, 6.23 mmol), $PdCl_2(PPh_3)_2$ (30.0 mg, 0.0425 mmol), CuI (16.0 mg, 0.0850 mmol) and $^{i}Pr_2NH$ (3.97 mL, 2.86 g, 28.3 mmol). The reaction was performed at room temperature overnight and the reaction mixture was passed through a celite silica plug with 20:80 ethyl acetate:pentane. Subsequent column chromatography eluted with 0-20% ethyl acetate in pentane gave the product as a white solid (0.759 g, 2.32 mmol, 82%). Mp 42-43 ^{o}C; (ESI) $(M+Ag)^+$ Found 434.9655, $C_{20}H_{16}AgCl_2$ requires 434.9668; ν_{max} 2942, 2871, 2769, 1624, 1432, 1339, 1181, 1152, 1072, 891, 728, 601, 544 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.30 (4H, d, J= 10.0 Hz, Ar*H*), 7.23 (4H, d, J= 10.0 Hz, Ar*H*), 2.44 (4H, m, CH_2*CH_2*CCAr), 1.75 (4H, m, CH_2*CH_2*CH_2*CH_2) ppm; ^{13}C NMR (126 MHz, $CDCl_3$) δ 134.61, 133.13, 128.55, 122.47, 90.89, 80.00, 27.84, 19.06 ppm; m/z ESI 435 $(M+Ag, 100\%)^+$.

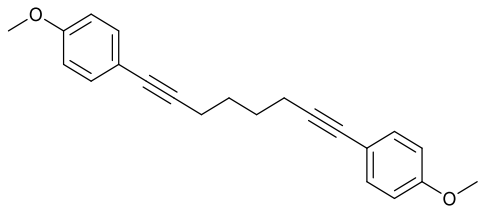
Iron(1,8-bis(4-chlorophenyl)octa-1,7-diyne) tricarbonyl.



This compound is novel. Iron(1,8-bis(4-chlorophenyl)octa-1,7-diyne) tricarbonyl was prepared via same method used previously to prepare Iron(1,8-diphenylocta-1,7-diyne) tricarbonyl using 1,8-bis(4-chlorophenyl)octa-1,7-diyne (0.500g, 1.53 mmol) and $Fe(CO)_5$ (620 µL, 4.59 mmol) in dry toluene (5.00 mL) at 130 ^{o}C overnight to give iron(1,8-bis(4-chlorophenyl)octa-1,7-diyne) tricarbonyl as a brown solid

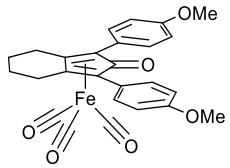
(0.708g, 1.43 mmol, 94%). Mp 152-153 ^{o}C; (ESI) $(M+H)^{+}$ Found 494.9855, $C_{24}H_{17}Cl_2FeO_4$ requires 494.9848; ν_{max} 2062, 2013, 1989, 1625, 1606, 1242, 1110, 1033, 894, 567, 535 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.74 (4 H, d, *ArH*) *7*.38 (4 H, d, Ar*H* 2.37 - 3.04 (4 H, m, $CH_2CH_2CH_2CH_2$) 1.96 (4 H, br. s., $CH_2CH_2CH_2CH_2$) ppm; ^{13}C NMR (126 MHz, $CDCl_3$) δ 214.58, 208.55, 169.02, 133.89, 130.75, 129.91, 128.72, 100.22, 80.27, 23.77, 22.19 ppm; m/z ESI 495 $(M+H, 100\%)^{+}$.

1,8-Bis(4-methoxyphenyl)octa-1,7-diyne.



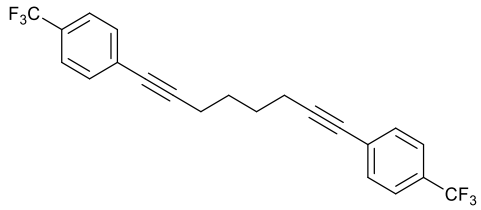
This compound is novel. 1,8-bis(4-methoxyphenyl)octa-1,7-diyne was prepared via the same method as 1,8-diphenylocta-1,7-diyne with 1,7-octadiyne (750mg, 7.07 mmol), 4-iodoanisole (3.31g, 14.1 mmol,), $PdCl_2(PPh_3)_2$ (74.0 mg, 0.106mmol), CuI (40.0mg, 0.212 mmol) and $^{i}Pr_2NH$ (7.15 g, 70.6 mmol) to give 1,8-bis(4-methoxyphenyl)octa-1,7-diyne as a white solid(1.77g, 5.56 mmol, 79%). Mp 39-40 ^{o}C; (ESI) $(M+H)^{+}$ Found 319.1694, $C_{22}H_{23}O_2$ requires 319.1693; ν_{max} 2998, 2937, 2903, 2861, 2838, 1605, 1568, 1508, 1440, 1289, 1241, 1172, 1109, 1029, 835, 823, 797, 662, 536 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.33 (4 H, d, J=8.8 Hz, Ar*H*), 6.81 (4 H, d, J=8.8 Hz, Ar*H*), 3.79 (6 H, s, OCH_3), 2.35 (4 H, m, $CH_2CH_2CH_2CH_2$), 1.75 (4 H, m, $CH_2CH_2CH_2CH_2$) ppm; ^{13}C NMR (126 MHz, $CDCl_3$) δ 159.04, 132.89, 116.95, 113.82, 88.24, 80.59, 55.27, 28.04, 19.04 ppm; m/z ESI 319 $(M+H, 100\%)^{+}$.

Tricarbonyl(1,8-bis(4-methoxyphenyl)octa-1,7-diyne)iron.



This compound is novel. Tricarbonyl(1,8-bis(4-methoxyphenyl)octa-1,7-diyne)iron was prepared via the same procedure used previously. In an oven dried pressure tube, 1,8-bis(4-methoxyphenyl)octa-1,7-diyne (500 mg, 1.57 mmol) was placed in dry toluene (5.00 mL) with $Fe(CO)_5$ (637 µl, 4.72 mmol) and the solution was vigorously degassed with a N_2 line for 15 minutes. The tube was then sealed and heated with stirring to 130 °C overnight. The product was isolated as brown solid (726 mg, 1.49 mmol, 95%). Mp 166-167 °C; Found (ESI) $(M+H)^+$ 487.0842, $C_{26}H_{23}FeO_6$ requires 487.0839; ν_{max} 2941, 2054, 1988, 1618, 1580, 1510, 1451, 1409, 1369, 1284, 1233, 1179, 1036, 896, 846, 662, 649, 627, 604, 584, 570, 529, 499, 459 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$) δ 7.73 (4 H, d, *J*=10.0 Hz, Ar*H*), 6.91 (4 H, d, *J*=10.0 Hz,Ar*H*), 3.82 (6 H, s, O*CH₃*), 2.86 (4 H, m, *CH₂*), 1.92 (4 H, br. s., *CH₂*) ppm; ^{13}C NMR (126 MHz, $CDCl_3$) δ 209.34, 169.34, 159.13, 130.84, 121.90, 113.88, 99.70, 81.85, 55.29, 23.88, 22.33 ppm; m/z 487 $(M+H)^+$, 509 (M+Na, 100%)$^+$.

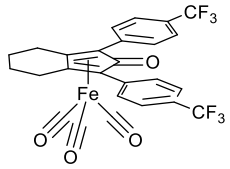
1,8-Bis(4-(trifluoromethyl)phenyl)octa-1,7-diyne.



This compound is novel. 1,8-Bis(4-(trifluoromethyl)phenyl)octa-1,7-diyne was synthesised with same procedure as previously used to synthesise 1,8-diphenylocta-1,7-diyne with 1,7-octadiyne (375 µL, 300 mg, 2.83 mmol), 4-iodobenzotrifluoride (916 µL, 1.70 g 6.23 mmol), $PdCl_2(PPh_3)_2$ (30.0 mg, 0.0425 mmol), CuI (16.0 mg, 0.0850 mmol) and $^iPr_2NH$ (3.97 mL, 2.86 g, 28.3 mmol) to give 1,8-bis(4-(trifluoromethyl)phenyl)octa-1,7-diyne as a white solid after column chromatography eluted with 0-20% ethyl acetate in hexane (0.780 g, 1.98 mmol,

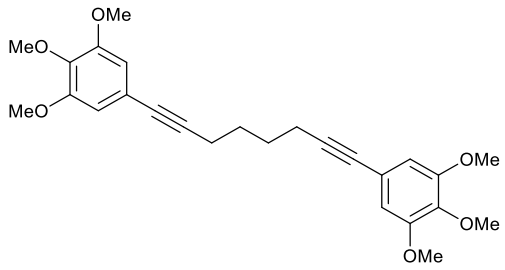
70%). Mp 35-36 °C; (ESI) Found 501.0212, $C_{22}H_{16}AgF_6$ requires 501.0202; ν_{max} 2073, 2023, 1995, 1659, 1605, 1289, 1135, 1075, 919, 585, 529 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$) δ 7.51 - 7.59 (4H, d, *J*= 8.0 Hz, Ar*H*) 7.43 - 7.51 (4 H, d, *J*= 8.0 Hz, Ar*H*) 2.13 - 2.80 (4 H, m, $CH_2CH_2CH_2CH_2$) 1.59 - 1.95 (4 H, m, $CH_2CH_2CH_2CH_2$) ppm; ^{13}C NMR (126 MHz, $CDCl_3$) δ 131.79, 129.36, 127.76, 125.20, 123.65, 92.52, 79.94, 27.69, 19.04 ppm; m/z (ESI) 501 (M+Ag, 100%).

Tricarbonyl(1,8-bis(4-(trifluoromethyl)phenyl)octa-1,7-diyne)iron.



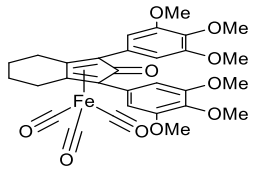
This compound is novel. Tricarbonyl(1,8-bis(4-(trifluoromethyl)phenyl)octa-1,7-diyne)iron was synthesised via the procedure previously used with 1,8-bis(4-(trifluoromethyl)phenyl)octa-1,7-diyne (500 mg, 1.27 mmol) and $Fe(CO)_5$ (513 µl, 3.81 mmol) to give tricarbonyl(1,8-bis(4-(trifluoromethyl)phenyl)octa-1,7-diyne)iron as a (give form) (690 mg, 1.23 mmol, 97%). Mp 155-156 °C; Found (ESI) $C_{26}H_{16}F_6FeNaO_4$ 585.0196, requires 585.0195; ν_{max} 2943, 2070, 2009, 1640, 1564, 1510, 1451, 1424, 1376, 1288, 1210, 1177, 1036, 896, 846, 662, 649, 499, 459 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$) 7.93 (4H, m, *J*= 10.0 Hz, Ar*H*) 7.62 (4H, m, *J*= 10.0 Hz, Ar*H*) 2.79 (4H, m, CH_2) 1.98 (4H, m, CH_2) ppm; ^{13}C NMR (126 MHz, $CDCl_3$) δ 207.08 - 208.91, 167.80 - 169.82, 134.92 - 135.88, 129.60 - 129.95, 129.76, 124.90 - 126.08, 120.52 - 127.39, 96.13 - 105.78, 78.42 - 84.43, 23.02 - 25.53, 21.58 - 22.72 ppm; m/z (ESI) 585 (M+Na,100%).

1,8-Bis(3,4,5-trimethoxybenzene)octa-1,7-diyne.



This compound is novel. In a dried and degassed (N_2) 100 mL round-bottomed flask equipped with a Findenser, 1,7-octadiyne (1.00 g, 9.42 mmol) and 5-bromo-1,2,3-trimethoxybenzene (5.121 g, 20.7 mmol) were placed in triethylamine (25 mL) with stirring via magnetic stirrer bar. $PdCl_2(PPh_3)_2$ (100 mg, 0.142 mmol) and CuI (26 mg, 0.137 mmol) were added and the reaction was stirred at 50 ^oC for two days. The reaction mixture was purified via column chromatography eluted with 0-50% ethyl acetate in pentane to give the product as a white crystalline solid (0.507 g, 1.16 mmol, 12%). Mp 51-52 ^oC; ν_{max} 2956, 2918, 2876, 2861, 2810, 1621, 1568, 1521, 1444, 1289, 1235, 1172, 1109, 1012, 829, 797, 620, 575, 491 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 6.64 (4 H, s, Ar*H*) 3.84 (s, 18 H, ArO*Me*) 2.48 (m, 4 H, $CH_2CH_2CH_2CH_2$) 1.79 (m, 4 H, $CH_2CH_2CH_2CH_2$) ppm; ^{13}C NMR (101 MHz, $CDCl_3$) δ 152.97, 138.21, 118.97, 108.64, 88.87, 80.87, 60.91, 56.05, 27.92, 18.99 ppm; m/z 461 (M+H, 100%)$^+$.

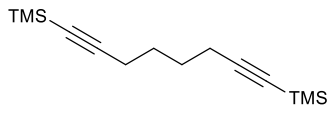
Tricarbonyl(1,8-bis(3,4,5-trimethoxybenzene)octa-1,7-diyne)iron.



This compound is novel. Tricarbonyl(1,8-bis(3,4,5-trimethoxybenzene)octa-1,7-diyne)iron was synthesised via the same procedure as iron(1,8-diphenylocta-1,7-diyne) tricarbonyl with 1,8-bis(3,4,5-trimethoxybenzene)octa-1,7-diyne (0.400 g, 0.913 mmol) and $Fe(CO)_5$ (537 µL, 800 mg, 2.74 mmol) to give the product a yellow solid (0.454 mg, 0.897 mmol, 98%). Mp 167-168 ^oC; Found (ESI) $C_{30}H_{30}FeNaO_{10}$

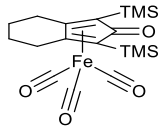
629.1079, requires 629.1081; ν_{max} 2941, 2837, 2052, 1987, 1619, 1606, 1514, 1439, 1249, 1179, 1026, 810, 571, 491 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.03 (4 H, s, Ar*H*) 3.88 (s, 18 H, ArO*Me*) 2.82 - 2.91 (d, 2 H, *CH₂*) 2.69 - 2.79 (d, 2 H, *CH₂*) 1.96 (m, 4 H, *CH₂*) ppm; ^{13}C NMR (126 MHz, $CDCl_3$) δ 209.15, 169.58, 152.94, 137.86, 126.57, 106.98, 99.95, 82.10, 60.84, 56.08, 23.89, 22.31 ppm; m/z 629 (M+Na, 100%).

1,8-Bis(trimethylsilyl)octa-1,7-diyne:



This compound is known and fully characterised.[3, 8, 43] In a dried and degassed 250 mL round-bottom flask, under N_2, $Zn(OTf)_2$ (335 mg, 0.922 mmol) and NEt_3 (7.70 mL, 5.59 g, 55.3 mmol) were dissolved in anhydrous DCM (50.0 mL). 1,7-Octadiyne (2.44 mL, 1.96 g, 18.4 mmol) was added in anhydrous DCM (15.0 mL) under N_2 and TMSOTf (10.0 mL, 12.3 g, 55.3 mmol) was added in anhydrous DCM (15.0 mL) under N_2 slowly in an ice bath. Heavy white fumes were produced, which dispersed to give a red/brown solution. The reaction was stirred overnight at room temperature, quenched with NH_4Cl and extracted with Et_2O (3x 50 mL). The organic fraction was dried with anhydrous Na_2SO_4, filtered and solvent removed via a rotary evaporator to give a brown oil. 1,8-Bis(trimethylsilyl)octa-1,7-diyne was isolated through column chromatography eluted with pentane to give a clear solid (3.35 g, 0.727 mmol, 73%). ^{1}H NMR (300 MHz, $CDCl_3$) δ 2.20 - 2.32 (14 H, m, $CH_2CH_2CH_2CH_2$), 1.57 - 1.68 (4 H, m, $CH_2CH_2CH_2CH_2$), 0.15 (18 H, s, $Si(CH_3)_3$) ppm.

Tricarbonyl(1,8-bis(trimethylsilyl)octa-1,7-diyne)iron:

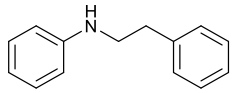


This compound is known and has been fully characterised.[4, 8] Tricarbonyl(1,8-bis(trimethylsilyl)octa-1,7-diyne was synthesised through the general procedure

using 1,8-bis(trimethylsilyl)octa-1,7-diyne (500 mg, 2.00 mmol) and $Fe(CO)_5$ (792 µL, 1.18g, 6.00 mmol). Tricarbonyl(1,8-bis(trimethylsilyl)octa-1,7-diyne was isolated through column chromatography eluted with ethyl acetate 0-5% in pentane to give a yellow solid (610 mg, 1.46 mmol, 73%). ^{1}H NMR (500 MHz, $CDCl_3$) δ 2.57 (4 H, m, C*H*$_2$CH$_2$CH$_2$C*H*$_2$), 1.83 (4 H, m, CH$_2$C*H*$_2$C*H*$_2$CH$_2$), 0.28 (18 H, br. s., Si(C*H*$_3$)$_3$); ^{13}C NMR (126 MHz, $CDCl_3$) δ ppm 209.04 (q), 181.20 (q), 110.99 (q), 71.71 (q), 24.75, 22.38, -0.31 ppm; m/z 419 (M+H, 100%).

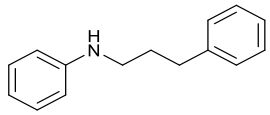
(3.3) Synthesis of Aniline-based Amines

N-phenethylaniline:



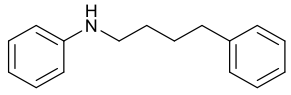
This compound is known and has been fully characterised.[44] *N*-Phenethylaniline was synthesised via the same procedure as previously described with 2-phenylethanol (122 µL, 122 mg, 1.00 mmol) and aniline (182 µL, 186 mg, 2.00 mmol). Tricarbonyl(1,8-bis(4-methoxyphenyl)octa-1,7-diyne)iron (48.6 mg, 0.100 mmol) with trimethylamine N-oxide (6.75 mg, 0.09 mmol) was used. Column chromatography, eluted with 0-5% ethyl acetate in pentane, gave the product as a colourless oil (52 mg, 0.264 mmol, 26%). Found (ESI), M^+ + H 198.1280, $C_{14}H_{16}N$ requires 198.1277; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.25 - 7.40 (2 H, m, Ar*H*) 7.09 - 7.24 (5 H, m, Ar*H*) 6.69 (1 H, t, *J*=8.0 Hz, Ar*H*) 6.58 (2 H, d, *J*=8.0 Hz, Ar*H*) 3.62 (1 H, br. s., N*H*) 3.36 (2 H, t, *J*=7.0 Hz, C*H*$_2$) 2.87 (2 H, t, *J*=7.0 Hz, C*H*$_2$) ppm; ^{13}C NMR (101 MHz, $CDCl_3$) δ 148.13, 139.45, 129.40, 128.91, 128.72, 126.54, 117.56, 113.10, 45.14, 35.62 ppm; m/z (EI) 198 (M^+ + H, 100%).

N-(3-phenylpropyl)aniline:



This compound is known, but has not been fully characterised.[44] *N*-(3-Phenylpropyl)aniline was synthesised via the same procedure as previously described with 3-phenyl-1-propanol (136 mg, 1.00 mmol), aniline (182 µL, 186 mg,2.00 mmol). Tricarbonyl(1,8-bis(4-methoxyphenyl)octa-1,7-diyne)iron (48.6 mg, 0.100 mmol) with trimethylamine N-oxide (6.75 mg, 0.09 mmol) was used. Column chromatography eluted with 0-5% ethyl acetate in pentane gave the product as a colourless oil (84.0 mg, 0.398 mmol, 40%). Found (ESI) 212.1436, $C_{15}H_{18}N$ requires 212.1434; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.23 - 7.33 (2 H, m, Ar*H*), 7.10 - 7.23 (5 H, m, Ar*H*), 6.68 (1 H, t, *J*=7.3 Hz, Ar*H*), 6.57 (2 H, d, *J*=7.6 Hz, Ar*H*), 3.59 (1 H, br. s., N*H*), 3.14 (2 H, t, *J*=6.9 Hz, CH_2), 2.73 (2 H, t, *J*=7.5 Hz, CH_2), 1.95 (2 H, quin, *J*=7.3 Hz, CH_2) ppm; ^{13}C NMR (75 MHz, $CDCl_3$) δ 148.35, 141.68, 129.24, 128.43, 125.97, 117.24, 112.76, 43.43, 33.42, 31.096 ppm; m/z (EI) 212 (M^+ + H, 100%).

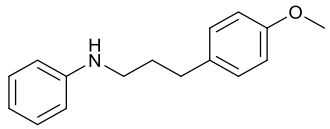
N-(4-phenylbutyl)aniline:



This compound is known, but not fully characterised.[45] *N*-(4-Phenylbutyl)aniline was synthesised via the same procedure as previously described with 4-phenyl-1-butanol (152 µL, 150 mg, 1.00 mmol), aniline (182 µL, 186 mg, 2.00 mmol). Tricarbonyl(1,8-bis(4-methoxyphenyl)octa-1,7-diyne)iron (48.6 mg, 0.100 mmol) with trimethylamine N-oxide (6.75 mg, 0.09 mmol) was used. Column chromatography eluted with 0-5% ethyl acetate in pentane gave the product as a colourless oil (102 mg, 0.453 mmol, 45%). Found (ESI) 226.1589, $C_{16}H_{20}N$ requires 226.1590; ν_{max} 3399, 2930, 2857, 1601, 1543, 1249, 746, 700 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.23 - 7.38 (2 H, m, Ar*H*), 7.03 - 7.22 (5 H, m, Ar*H*), 6.7 (1 H, t, *J*=7.2 Hz, Ar*H*), 6.57 (2 H, d, *J*=7.8 Hz, Ar*H*), 3.54 (1 H, br. s., N*H*), 3.11 (2 H, t, *J*=6.6 Hz, CH_2), 2.65 (2 H, t, *J*=7.2 Hz, CH_2), 1.54 - 1.84 (4 H, m, CH_2) ppm; ^{13}C NMR (75 MHz,

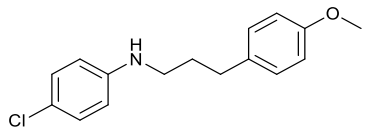
$CDCl_3$) δ 148.49, 142.26, 129.28, 128.47, 128.40, 125.87, 117.20, 112.74, 43.88, 35.71, 29.20, 28.98 ppm; m/z (ESI) 226 (M^++ 1, 100%).

N-(3-(4-methoxyphenyl)propyl)aniline:



This compound is known and fully characterised.[46] *N*-3-(4-Methoxyphenyl)propyl)aniline was synthesised via the previously described method using 3-(4-methoxyphenyl)-1-propanol (166 mg, 1.00 mmol) and aniline (182 µL, 2.00 mmol,). Tricarbonyl(1,8-bis(4-methoxyphenyl)octa-1,7-diyne)iron (48.6 mg, 0.100 mmol) with trimethylamine N-oxide (6.75 mg, 0.09 mmol) was used. Column chromatography eluted with 0-5% ethyl acetate in pentane afforded the product as a colourless oil (226mg, 0.938 mmol, 94%). Found (ESI) 242.1536, $C_{16}H_{20}NO$ requires 242.1539; ν_{max} 3399, 2931, 2834, 1602, 1509, 1243, 1177, 1113, 1033, 813, 749, 693 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.13 - 7.20 (2 H, m, Ar*H*) 7.11 (2 H, d, *J*=8.5 Hz, Ar*H*) 6.83 (2 H, d, *J*=8.5 Hz, Ar*H*) 6.68 (1 H, t, *J*=7.3 Hz, Ar*H*) 6.57 (2 H, d, *J*=7.6 Hz, Ar*H*) 3.78 (3 H, s, *OCH*$_3$) 3.59 (1 H, br. s., N*H*) 3.12 (2 H, t, *J*=7.0 Hz, C*H*$_2$) 2.67 (2 H, t, *J*=7.6 Hz, C*H*$_2$) 1.91 (2 H, quin, *J*=7.3 Hz, C*H*$_2$) ppm; ^{13}C NMR (126 MHz, $CDCl_3$) δ 157.88, 148.40, 133.72, 129.31, 129.24, 117.20, 113.86, 112.75, 55.29, 43.37, 32.48, 31.31 ppm; m/z (ESI) 242 (M^+ + 1, 100%).

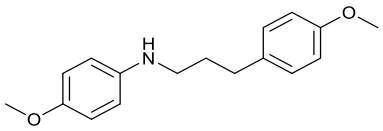
4-Chloro-*N*-(3-(4-methoxyphenyl)propyl)aniline:



This compound is known, but not fully characterised.[47] 4-Chloro-*N*-(3-(4-methoxyphenyl)propyl)aniline was synthesised via the previously described method using 3-(4-methoxyphenyl)-1-propanol (166 mg, 1.00 mmol) and 4-chloroaniline (255 mg, 2.00 mmol). Tricarbonyl(1,8-bis(4-methoxyphenyl)octa-1,7-diyne)iron

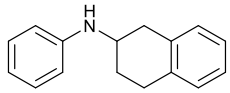
(48.6 mg, 0.100 mmol) with trimethylamine N-oxide (6.75 mg, 0.09 mmol) was used. Column chromatography eluted with 0-5% ethyl acetate in pentane gave the product as a clear oil (262 mg, 0.953 mmol, 95%). Found 276.1151 & 278.1121, C16H19ClNO requires 276.1150 & 278.1120; ν_{max} 3402, 2933, 2860, 2835, 1598, 1509, 1261, 1176, 1086, 1003, 816 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.09 (4 H, m, *J*=8.7, 4.6 Hz, Ar*H*) 6.83 (2 H, d, *J*=8.5 Hz, Ar*H*) 6.46 (2 H, d, *J*=8.9 Hz, Ar*H*) 3.78 (3 H, s, OC*H*$_3$) 3.60 (1 H, br. s., N*H*) 3.08 (2 H, t, *J*=7.0 Hz, NC*H*$_2$) 2.65 (2 H, t, *J*=7.6 Hz, C*H*$_2$) 1.89 (2 H, quin, *J*=7.3 Hz, C*H*$_2$) ppm; ^{13}C NMR (126 MHz, $CDCl_3$) δ 157.93, 146.92, 133.52, 129.29, 129.03, 121.67, 113.89, 113.77, 55.29, 43.44, 32.42, 31.11 ppm; m/z (ESI) 276 (M^+ + H, 100%), 278 (M^+ + H, 40%).

4-Methoxy-*N*-(3-(4-methoxyphenyl)propyl)aniline:



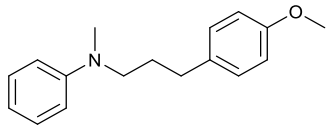
This compound is known, but not fully characterised.[48] 4-Methoxy-*N*-(4-(methoxyphenyl)propyl)aniline was synthesised via the previously described method with 3-(4-methoxyphenyl)-1-propanol (166 mg, 1.00 mmol) and anisidine (246 mg, 2.00 mmol). Tricarbonyl(1,8-bis(4-methoxyphenyl)octa-1,7-diyne)iron (48.6 mg, 0.100 mmol) with trimethylamine N-oxide (6.75 mg, 0.09 mmol) was used. Column chromatography eluted with 0-5% ethyl acetate in pentane afforded the product as a colourless oil (268mg, 0.989 mmol, 99%). ν_{max} 3401, 2932, 2834, 1602, 1509, 1243, 1177, 1113, 1033, 812, 748, 693 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.11 (2 H, d, *J*=8.5 Hz, Ar*H*) 6.83 (2 H, d, *J*=8.5 Hz, Ar*H*) 6.76 (8 H, d, *J*=8.9 Hz, Ar*H*) 6.55 (2 H, d, *J*=8.9 Hz, Ar**H**) 3.79 (3 H, s, OC*H*$_3$) 3.74 (12 H, s, OC*H*$_3$) 3.08 (2 H, t, *J*=7.3 Hz, NC*H*$_2$) 2.66 (2 H, t, *J*=7.3 Hz, C*H*$_2$) 1.89 (2 H, q, *J*=7.3 Hz, $CH_2CH_2CH_2$) ppm; ^{13}C NMR (126 MHz, $CDCl_3$) δ 157.85, 152.05, 142.65, 133.79, 129.29, 114.90, 114.12, 113.84, 55.84, 55.28, 44.44, 32.51, 31.41 ppm; m/z (ESI) 272 (M^+ + H, 100%).

N-Phenyl-1,2,3,4-tetrahydronaphthalen-2-amine.



This compound is known, but not fully characterised.[49] *N*-Phenyl-1,2,3,4-tetrahydronaphthalen-2-amine was prepared via the general procedure using aniline (182 µL, 186 mg, 2.00 mmol) and β-tetralol (148 mg, 1.00 mmol, 1.00). Tricarbonyl(1,8-bis(4-methoxyphenyl)octa-1,7-diyne)iron (48.6 mg, 0.100 mmol) with trimethylamine N-oxide (6.75 mg, 0.09 mmol) was used. Flash chromatography with 0-5% ethyl acetate in pentane gave *N*-phenyl-1,2,3,4-tetrahydronaphthalen-2-amine as a colourless oil (131 mg, 0.587 mmol, 59%). Found (ESI) 224.1432, $C_{16}H_{18}N$ requires 224.1434; ν_{max} 3354, 3033, 2924, 2838, 2059, 1992, 1600, 1497, 1438, 1249, 1176, 1176, 1028, 994, 878, 828, 748, 692, 618, 590, 503 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.03 - 7.23 (6 H, m, Ar*H*) 6.58 - 6.77 (3 H, m, Ar*H*) 3.75 - 3.92 (1 H, m, NC*H*) 3.69 (1 H, br. s., N*H*) 3.22 (1 H, dd, *J*=16.2, 4.5 Hz, C*H*H) 2.92 (2 H, t, *J*=6.5 Hz, ArCH_2) 2.69 (1 H, dd, *J*=16.2, 8.3 Hz, CH*H*) 2.10 - 2.29 (1 H, m, CH_2) 1.69 - 1.87 (1 H, m, CH_2) ppm; ^{13}C NMR (75 MHz, $CDCl_3$) δ 147.2, 135.9, 134.7, 129.5, 129.4, 128.8, 126.1, 125.9, 117.3, 113.4, 48.5, 36.5, 28.8, 27.5 ppm; m/z 224 (M+H, 100%).

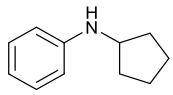
N-(3-(4-Methoxyphenyl)propyl)-*N*-methylaniline



This compound is known and fully characterised.[46] *N*-(3-(4-Methoxyphenyl)propyl)-*N*-methylaniline was prepared via the general procedure using N-methylaniline (217 µL, 214 mg, 2.00 mmol) and 3-(4-methoxyphenyl)-1-propanol (166 mg, 1.00 mmol). Tricarbonyl(1,8-bis(4-methoxyphenyl)octa-1,7-diyne)iron (48.6 mg, 0.100 mmol) with trimethylamine N-oxide (6.75 mg, 0.09 mmol) was used. Flash chromatography with 0-5% ethyl acetate in pentane gave *N*-(3-(4-methoxyphenyl)propyl)-*N*-methylaniline as a colourless oil (127 mg, 0.498 mmol,

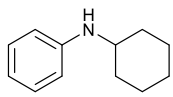
50%). Found (ESI) 256.1698, $C_{17}H_{21}NO$ requires 256.1696; ν_{max} 3412, 2932, 2813, 2060, 1998, 1602, 1506, 1318, 1244, 1178, 1032, 748, 692 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.20 (2 H, t, *J*=7.32 Hz, Ar*H*) 7.09 (2 H, d, *J*=8.0 Hz, Ar*H*) 6.82 (2 H, d, *J*=7.7 Hz, Ar*H*) 6.57 - 6.71 (3 H, m, Ar*H*) 3.78 (3 H, s, OCH_3) 3.31 (2 H, t, *J*=7.4 Hz, NCH_2) 2.90 (3 H, s, NCH_3) 2.58 (2 H, t, *J*=7.6 Hz, NCH_2) 1.87 (2 H, quin, *J*=7.5 Hz, $CH_2CH_2CH_2$) ppm; ^{13}C NMR (126 MHz, $CDCl_3$) δ 157.9, 149.4, 133.9, 129.3, 129.2, 116.0, 113.8, 112.3, 55.3, 52.2, 38.3, 32.4, 28.4 ppm; m/z 256 (M+H, 100%).

N-Cyclopentylaniline



This compound is known, but not fully characterised.[50] *N*-Cyclopentylaniline was prepared via the general procedure using aniline (182 µL, 186 mg, 2.00 mmol) and cyclopentanol (91 µL, 85 mg, 1.00 mmol). Tricarbonyl(1,8-bis(4-methoxyphenyl)octa-1,7-diyne)iron (48.6 mg, 0.100 mmol) with trimethylamine N-oxide (6.75 mg, 0.09 mmol) was used. Flash chromatography with 0-5% ethyl acetate in pentane gave *N*-cyclopentylaniline amine as a colourless oil (145 mg, 0.901 mmol, 90%). Found (ESI) 162.1277, $C_{11}H_{16}N$ requires 162.1277; ν_{max} 3406, 2955, 2868, 1602, 1504, 1256, 748, 692 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.16 (2 H, t, *J*=7.7 Hz, Ar*H*) 6.67 (1 H, t, *J*=7.3 Hz, Ar*H*) 6.60 (2 H, d, *J*=7.7 Hz, Ar*H*) 3.78 (1 H, quin, *J*=6.1 Hz, NC*H*) 3.63 (1 H, br. S, N*H*) 2.02 (2 H, m, *J*=12.4, 6.2 Hz, CH_2) 1.39 - 1.83 (6 H, m, CH_2) ppm; ^{13}C NMR (126 MHz, $CDCl_3$) δ 148.1, 129.2, 116.9, 113.2, 54.7, 33.6, 24.1 ppm; m/z 162 (M+H, 100%).

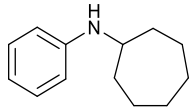
N-cyclohexylaniline:



This compound is known, but is not fully characterised.[45] Compound was synthesised via the general method from aniline (182 µL, 186 mg, 2.00 mmol) and

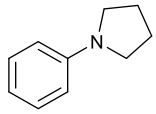
cyclohexane (105 µL, 100 mg, 1.00 mmol). Tricarbonyl(1,8-bis(4-methoxyphenyl)octa-1,7-diyne)iron (48.6 mg, 0.100 mmol) with trimethylamine N-oxide (6.75 mg, 0.09 mmol) was used. Flash chromatography eluted with 0-5% ethyl acetate in pentane gave N-cyclohexylaniline as a yellow oil (166 mg, 0.949 mmol, 95%). Found (ESI) 176.1438, $C_{12}H_{18}N$ requires 176.1434; ν_{max} 3367, 2925, 2851, 1600, 1500, 1451, 1255, 1177, 745, 691 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.07 - 7.20 (2 H, m, Ar*H*) 6.61 - 6.69 (1 H, m, Ar*H*) 6.56 (2 H, m, Ar*H*) 3.47 (1 H, br. s., N*H*) 3.23 (1 H, tt, *J*=10.2, 3.7 Hz, NC*H*) 1.94 - 2.12 (2 H, m, C*H*$_2$) 1.74 (2 H, m, C*H*$_2$) 1.55 - 1.68 (1 H, m, C*H*$_2$) 1.28 - 1.42 (2 H, m, C*H*$_2$) 1.04 - 1.27 (3 H, m, C*H*$_2$) ppm. ^{13}C NMR (126 MHz, $CDCl_3$) δ 147.5, 129.4, 116.9, 113.2, 51.8, 33.6, 26.1, 25.1 ppm; m/z 176 (M+H, 100%).

N-Phenylcycloheptanamine



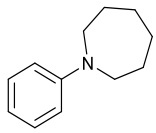
This compound is known, but not fully characterised.[51] *N*-Phenylcycloheptylanimine was prepared via the general procedure using aniline (182 µL, 186 mg, 2.00 mmol) and cyclopheptanol (238 mg, 1.00 mmol). Tricarbonyl(1,8-bis(4-methoxyphenyl)octa-1,7-diyne)iron (48.6 mg, 0.100 mmol) with trimethylamine N-oxide (6.75 mg, 0.09 mmol) was used. Flash chromatography with 0-2% ethyl acetate in pentane gave *N*-phenylcycloheptylanimine as a colourless oil (182 mg, 0.963 mmol, 96%). Found 190.1592, $C_{13}H_{20}N$ requires 190.1590; ν_{max} 3404, 2922, 1677, 1600, 1502, 1429, 1318, 1276, 1252, 1177, 745, 691 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.25 (2 H, t, *J*=7.9 Hz, Ar*H*) 6.75 (1 H, t, *J*=7.3 Hz, Ar*H*) 6.64 (2 H, d, *J*=7.8 Hz, Ar*H*) 3.65 (1 H, br. s., N*H*) 3.55 (1 H, m, NC*H*) 2.03 - 2.21 (2 H, m, C*H*$_2$) 1.48 - 1.88 (10 H, m, C*H*$_2$) ppm; ^{13}C NMR (126 MHz, $CDCl_3$) δ 147.4, 129.3, 116.8, 113.3, 53.7, 34.9, 28.5, 24.51 ppm; m/z 190 (M+H, 100%).

1-Phenylpyrrolidine.



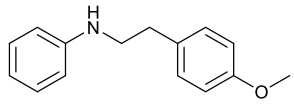
This compound is known and fully characterised.[45] 1-Phenylpyrrolidine was prepared via the general procedure using aniline (91 µL, 93 mg, 1.00 mmol) and 1,4-butanediol (177180? mg, 2.00 mmol). Tricarbonyl(1,8-bis(4-methoxyphenyl)octa-1,7-diyne)iron (48.6 mg, 0.100 mmol) with trimethylamine N-oxide (6.75 mg, 0.09 mmol) was used. Flash chromatography with 0-2% ethyl acetate in pentane gave 1-phenylpyrrolidine as a colourless oil (50 mg, 0.34 mmol, 34%). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.17 - 7.34 (2 H, m, Ar*H*) 6.65 (1 H, t, *J*=7.3 Hz, Ar*H*) 6.57 (11 H, d, *J*=7.9 Hz, Ar*H*) 3.28 (4 H, t, *J*=6.6 Hz, NCH_2) 2.00 (4 H, m, CH_2) ppm; ^{13}C NMR (126 MHz, $CDCl_3$) δ ppm 148.0, 129.1, 115.4, 111.6, 47.6, 25.5 ppm; m/z 148 (M+H, 100%).

1-Phenylazapine.



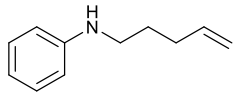
This compound is known and fully characterised.[52] 1-Phenylpyrrolidine was prepared via the general procedure using aniline (91. µL, 93 mg, 1.00 mmol) and 1,6-hexanediol (210 µL, 236 mg, 2.00 mmol). Tricarbonyl(1,8-bis(4-methoxyphenyl)octa-1,7-diyne)iron (48.6 mg, 0.100 mmol) with trimethylamine N-oxide (6.75 mg, 0.09 mmol) was used. Flash chromatography with 0-2% ethyl acetate in pentane gave 1-phenylpyrrolidine as a colourless oil (75 mg, 0.43 mmol, 43%). Found 176.1436, $C_{12}H_{18}N$ requires 176.1434; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.20 (2 H, dd, *J*=8.8, 7.2 Hz, Ar*H*) 6.69 (2 H, d, *J*=7.9 Hz, Ar*H*) 6.62 (1 H, t, *J*=7.3 Hz, Ar*H*) 3.41 - 3.50 (4 H, m, NCH_2) 1.72 - 1.85 (4 H, m, CH_2) 1.51 - 1.58 (4 H, m, CH_2) ppm; ^{13}C NMR (126 MHz, $CDCl_3$) δ 148.9, 129.2, 115.1, 111.1, 49.0, 27.8, 27.2 ppm; m/z (ESI) 176 (M+H, 100%).

N-(4-Methoxyphenethyl)aniline.



This compound is known, but not fully characterised.[53] N-(4-Methoxyphenethyl)aniline was prepared via the general procedure using aniline (182 µL, 186 mg, 2.00 mmol) and 4-methoxyphenethyl alcohol (152 mg, 1.00 mmol). Tricarbonyl(1,8-bis(4-methoxyphenyl)octa-1,7-diyne)iron (48.6 mg, 0.100 mmol) with trimethylamine N-oxide (6.75 mg, 0.09 mmol) was used. Flash chromatography with 0-5% ethyl acetate in pentane gave N-(4-methoxyphenethyl)aniline as a colourless oil (80 mg, 0.352 mmol, 35%). ν_{max} 3418, 2928, 1681, 1601, 1504, 1452, 1419, 1322, 1288, 1178, 1126, 1071, 1026, 930, 804, 747, 704, 666, 545 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$) δ 7.08 - 7.23 (5 H, m, Ar*H*) 6.86 (1 H, d, *J*=8.7 Hz, Ar*H*) 6.70 (1 H, t, *J*=7.3 Hz, Ar*H*) 6.61 (2 H, d, *J*=9.3 Hz, Ar*H*) 3.80 (3 H, s, OCH_3) 3.65 (1 H, br. s., N*H*) 3.36 (2 H, t, *J*=6.9 Hz, NHCH_2) 2.86 (2 H, t, *J*=6.9 Hz, CH_2Ar) ppm; ^{13}C NMR (126 MHz, $CDCl_3$) δ 158.2, 148.1, 131.3, 129.7, 129.3, 117.4, 114.0, 113.0, 55.3, 45.2, 34.6 ppm; m/z 227 (M+H, 100%).

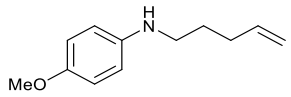
N-(pent-4-en-1-yl)aniline:



This compound is novel. *N*-(pent-4-en-1-yl)aniline was synthesised through the general procedure using aniline (182 µL, 186 mg, 2.00 mmol) and penten-1-ol (105 µL, 86.0 mg, 1.00 mmol). Tricarbonyl(1,8-bis(trimethylsilyl)octa-1,7-diyne)iron (42.0 mg, 0.100 mmol) was used with trimethylamine N-oxide (15.0 mg, 0.200 mmol). *N*-(pent-4-en-1-yl)aniline was isolated through column chromatography eluted with 0-20% ethyl acetate in pentane to give a light brown oil (128 mg, 0.748 mmol, 75%). Found 162.1278, $C_{11}H_{16}N$ requires 162.1277; ^1H NMR (500 MHz, $CDCl_3$) δ 7.17 (2 H, t, *J*=7.9 Hz, Ar*H*), 6.69 (1 H, t, *J*=7.3 Hz, Ar*H*), 6.60 (2 H, d, *J*=7.8 Hz, Ar*H*), 5.84 (1 H, ddt, *J*=17.0, 10.3, 6.6 Hz, CH_2CH=CH_2), 5.06 (1 H, dd, *J*=17.2, 1.7 Hz, CH=CH*H*), 5.00

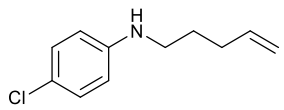
(1 H, d, *J*=10.2 Hz, CH=C*H*H), 3.61 (1 H, br. s., N*H*), 3.13 (2 H, t, *J*=7.1 Hz, NHCH_2), 2.17 (2 H, q, *J*=6.9 Hz, $CH_2CH_2CH{=}CH_2$), 1.72 (2 H, quin, *J*=7.3 Hz, $CH_2CH_2CH_2$) ppm; ^{13}C NMR (126 MHz, $CDCl_3$) δ 148.36, 138.04, 129.21, 117.15, 114.67, 112.69, 43.37, 31.28, 28.63 ppm; m/z (ESI) 162 (M+H, 100%).

4-Methoxy-*N*-(pent-4-en-1-yl)aniline



This compound is novel. 4-Methoxy-*N*-(pent-4-en-1-yl)aniline was synthesised via the general procedure using *p*-anisidine (245 mg, 2.00 mmol) and 4-penten-1-ol (86 mg, 1.00 mmol). Tricarbonyl(1,8-bis(trimethylsilyl)octa-1,7-diyne)iron (42.0 mg, 0.100 mmol) was used with trimethylamine N-oxide (15.0 mg, 0.2 mmol). The product was isolated via column chromatography with 0-40% ethyl acetate in pentane to give 4-methoxy-*N*-(pent-4-en-1-yl)aniline as a colourless oil (134 mg, 0.698 mmol, 70%). Found (ESI) 192.1395, $C_{12}H_{18}NO$ requires 192.1383; ν_{max} 3390, 2931, 2832, 1640, 1512, 1236, 1038 and 819 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$) δ 6.78 (2 H, d, *J*=8.9 Hz, Ar*H*) 6.58 (2 H, d, *J*=8.9 Hz, Ar*H*) 5.84 (1 H, ddt, *CH*=CH_2) 5.05 (1 H, d, *J*=17.0 Hz, CH=CH*H*) 4.99 (1 H, d, *J*=10.2 Hz, CH=C*H*H) 3.75 (3 H, s, OCH_3) 3.09 (2 H, t, *J*=8.7 Hz, NHCH_2) 2.17 (2 H, q, *J*=6.1 Hz, CH_2CH=CH_2) 1.70 (2 H, quin, *J*=7.3 Hz, $CH_2CH_2CH_2$) 1.46 - 1.91 (1 H , br. s., *NH*) ppm; ^{13}C NMR (126 MHz, $CDCl_3$) δ 152.03, 142.71, 138.14, 115.04, 114.93, 114.09, 55.86, 44.46, 31.35, 28.77 ppm; m/z (ESI) 192 (M+H, 100%).

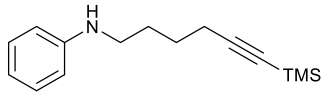
4-Chloro-*N*-(pent-4-en-1-yl)aniline:



This compound is novel. 4-Chloro-*N*-(pent-4-en-1-yl)aniline was synthesised through the general procedure using 4-chloroaniline (255 mg, 2.00 mmol) and penten-1-ol (105 µL, 86.0 mg, 1.00 mmol). Tricarbonyl(1,8-bis(trimethylsilyl)octa-

1,7-diyne)iron (42.0 mg, 0.100 mmol) was used with trimethylamine N-oxide (15.0 mg, 0.200 mmol). 4-Chloro-*N*-(pent-4-en-1-yl)aniline was isolated through column chromatography eluted with 0-20% ethyl acetate in pentane to give a light brown oil (82.0 mg, 0.421 mmol, 42%). Found 196.0886 + 198.0856, $C_{11}H_{15}ClN$ requires 196.0888 + 198.0858; ^{1}H NMR (600 MHz, $CDCl_3$) δ 6.96 (2 H, d, *J*=8.3 Hz, Ar*H*), 6.36 (2 H, d, *J*=8.3 Hz, Ar*H*), 5.68 (1 H, ddt, *J*=17.0, 10.3, 6.6 Hz, C*H*=CH_2), 4.91 (1 H, d, *J*=17.3 Hz, CH=CH*H*), 4.85 (1 H, d, *J*=10.2 Hz, CH=C*H*H (cis)), 3.49 (6 H, br. s., N*H*), 2.94 (2 H, t, *J*=7.0 Hz, NHCH_2), 2.01 (2 H, q, *J*=7.1 Hz, $CH_2CH_2CH{=}CH_2$), 1.55 (2 H, quin, *J*=7.1 Hz, $CH_2CH_2CH_2$) ppm; ^{13}C NMR (151 MHz, $CDCl_3$) δ 146.75, 137.71, 128.86, 121.49, 115.07, 113.56, 43.32, 31.07, 28.32 ppm; m/z 196 (M+H (^{35}Cl), 100%), 198 (M + H (^{37}Cl), 33%).

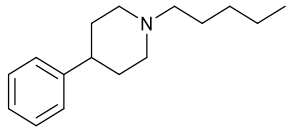
N-(6-(trimethylsilyl)hex-5-yn-1-yl)aniline:



This compound is novel. *N*-(6-(trimethylsilyl)hex-5-yn-1-yl)aniline was synthesised through the general procedure using aniline (182 µL, 186 mg, 2.00 mmol) and 6-(trimethylsilyl)hex-5-yn-1-ol (166 mg, 1.00 mmol). Tricarbonyl(1,8-bis(trimethylsilyl)octa-1,7-diyne)iron (42.0 mg, 0.100 mmol) was used with trimethylamine N-oxide (15.0 mg, 0.200 mmol). *N*-(6-(trimethylsilyl)hex-5-yn-1-yl)aniline was isolated via column chromatography to give a colourless oil (196 mg, 0.799 mmol, 80%). Found 245.1671, $C_{15}H_{24}NSi$ requires 246.1673; ν_{max} 3385, 2933, 2169, 1601 cm^{-1} ; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.21 (2 H, t, *J*=7.6 Hz, Ar*H*) 6.73 (1 H, t, *J*=7.3 Hz, Ar*H*), 6.64 (2 H, d, *J*=8.1 Hz, Ar*H*), 3.17 (2 H, t, *J*=7.0 Hz, NHCH_2), 2.32 (2 H, t, *J*=7.0 Hz, CH_2CCSi), 1.77 (2 H, quin, *J*=7.0 Hz, C$H_2CH_2CH_2$CC), 1.67 (2 H, quin, *J*=7.0 Hz, CH_2CH_2CC), 0.20 (9 H, s, Si(CH_3)$_3$) ppm; ^{13}C NMR (126 MHz, $CDCl_3$) δ 148.27, 129.17, 117.10, 112.60, 106.93, 84.85, 43.34, 28.51, 26.07, 19.59, 0.10 ppm; m/z (ESI) 246 (M+H, 100%).

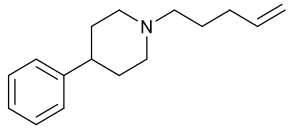
(3.4) Synthesis of Piperidine-based Amines

1-Pentyl-4-phenylpiperidine.



This compound is novel. 1-Pentyl-4-phenylpiperidine was synthesised via the general procedure from 4-phenylpiperidine (161 mg, 1.00 mmol) and 1-pentanol (217 µL, 176 mg, 2.00 mmol). Tricarbonyl(1,8-bis(trimethylsilyl)octa-1,7-diyne)iron (42.0 mg, 0.100 mmol) was used with trimethylamine N-oxide (15.0 mg, 0.2 mmol). The compound was purified via column chromatography eluted with 0-40% ethyl acetate in pentane to give (name) as a colourless oil (225 mg, 0.974 mmol, 97%). Found (EI) 232.2068, $C_{16}H_{26}N$ requires 232.2060; ν_{max} 2954, 2871, 1662, 1454, 1376, 1138, 1097, 1067, 992, 755, 698 and 534 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.12 - 7.41 (5 H, m, Ar*H*), 3.06 (2 H, d, *J*=11.6 Hz, N*CH*$_2$), 2.49 (1 H, ddd, *J*=15.7, 10.5, 5.7 Hz, Ph*CH*), 2.27 - 2.42 (2 H, m, N*CH*$_2$CH$_2$CH$_2$), 2.02 (2 H, td, *J*=11.0, 4.2 Hz, N*CH*$_2$), 1.72 - 1.91 (4 H, m, C*H*$_2$), 1.47 - 1.62 (2 H, m, CH$_2$*CH*$_2$CH$_2$), 1.20 - 1.44 (4 H, m, *CH*$_2$), 0.91 (3 H, t, *J*=7.1 Hz, 3 H, CH$_2$*CH*$_3$) ppm; ^{13}C NMR (126 MHz, $CDCl_3$) δ 146.5, 128.4, 126.9, 126.1, 59.3, 54.5, 42.9, 33.5, 30.0, 26.8, 22.7, 14.1 ppm; m/z (ESI) 232 (M+H, 100%).

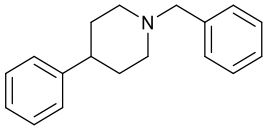
1-(Pent-4-en-1-yl)-4-phenylpiperidine.



This compound is novel. 1-(pent-4-en-1-yl)-4-phenylpiperidine was synthesised via the general method using 4-phenylpiperidine (161 mg, 1.00 mmol) and 4-penten-1-ol (208 µL, 172 mg, 2.00 mmol). Tricarbonyl(1,8-bis(trimethylsilyl)octa-1,7-diyne)iron (42.0 mg, 0.100 mmol) was used with trimethylamine N-oxide (15.0 mg, 0.2 mmol). The product was isolated using column chromatography eluted with 0-30% ethyl acetate in pentane to give 1-(pent-4-en-1-yl)-4-phenylpiperidine as a

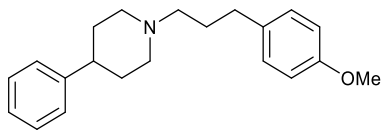
colourless oil (218 mg, 0.952 mmol, 95%). Found (ESI) 230.1901, $C_{16}H_{24}N$ requires 230.1903; ν_{max} 2933, 2801, 2763, 1640, 1494, 1452, 1376, 1132, 993, 910, 756 and 699 cm^{-1} ; ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.30 - 7.34 (2 H, m, Ar*H*), 7.24 - 7.29 (2 H, m, Ar*H*), 7.19 - 7.24 (1 H, m, Ar*H*), 5.87 (1 H, ddt, *J*=17.0, 10.2, 6.7, Hz, CH_2*CH*=CH_2), 5.07 (1 H, dd, *J*=17.1, 1.7 Hz, CH=*CH*$_2$), 5.00 (1 H, d, *J*=10.1 Hz, CH=*CH*$_2$), 3.09 (2 H, d, *J*=11.6 Hz, N*CH*$_2$), 2.52 (1 H, tt, *J*=10.5, 5.5 Hz, Ph*CH*), 2.38 - 2.44 (2 H, m, N*CH*$_2$$CH_2$$CH_2$), 2.12 (2 H, q, *J*=7.1 Hz, CH_2*CH*$_2$CH=CH_2), 2.04 - 2.10 (2 H, m, N*CH*$_2$$CH_2$), 1.79 - 1.91 (4 H, m, PhCH*CH*$_2$), 1.68 (2 H, quin, *J*=7.7 Hz, CH_2*CH*$_2$$CH_2$); ^{13}C NMR (126 MHz, $CDCl_3$) δ 146.51, 138.58, 128.43, 126.90, 126.11, 114.62, 58.65, 54.51, 42.87, 33.58, 31.89, 26.35 ppm; m/z 230 (M+H, 100%).

1-Benzyl-4-phenylpiperidine.



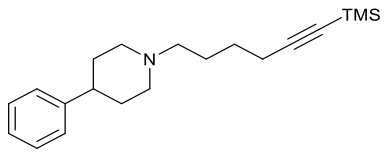
This compound is novel. 1-Benzyl-4-phenylpiperidine was synthesised via the general procedure using 4-phenylpiperidine (161 mg, 1.00 mmol) and benzyl alcohol (207 µL, 216 mg, 2.00 mmol). Tricarbonyl(1,8-bis(trimethylsilyl)octa-1,7-diyne)iron (42.0 mg, 0.100 mmol) was used with trimethylamine N-oxide (15.0 mg, 0.2 mmol). The product was isolated via column chromatography eluted with 0-30% ethyl acetate in pentane to give 1-benzyl-4-phenylpiperidine as a colourless oil (239 mg, 0.952 mmol, 95%). Found (EI) 252.1748, $C_{18}H_{22}N$ requires 252.1747; ν_{max} 2934, 2799, 2756, 1494, 1453, 1366, 991, 738, 698 cm^{-1} ; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.14 - 7.37 (10 H, m, Ar*H*) 3.54 (2 H, s, *CH*$_2$Ph) 3.01 (2 H, d, *J*=11.6 Hz, *CH*$_2$N*CH*$_2$) 2.42 - 2.55 (1 H, m, Ph*CH*$(CH_2)_2$) 2.02 - 2.13 (2 H, m, *CH*$_2$N*CH*$_2$) 1.74 - 1.86 (4 H, m, CH*CH*$_2$$CH_2$) ppm; ^{13}C NMR (126 MHz, $CDCl_3$) δ 146.76, 138.67, 129.50, 128.61, 128.41, 127.20, 127.12, 126.30, 63.75, 54.52, 42.94, 33.74 ppm; m/z (ESI) 252 ($M+H^+$, 100%).

1-(3-(4-Methoxyphenyl)propyl)-4-phenylpiperidine.



This compound is novel. 1-(3-(4-Methoxyphenyl)propyl)-4-phenylpiperidine was synthesised via the general procedure using 4-phenylpiperidine (161 mg, 1.00 mmol) and 3-(4-methoxyphenyl)-1-propanol (332 mg, 2.00 mmol). Tricarbonyl(1,8-bis(trimethylsilyl)octa-1,7-diyne)iron (42.0 mg, 0.100 mmol) was used with trimethylamine N-oxide (15.0 mg, 0.2 mmol). The 1-(3-(4-methoxyphenyl)propyl)-4-phenylpiperidine was isolated via column chromatography eluted with 0-50% ethyl acetate in pentane to give 1-(3-(4-Methoxyphenyl)propyl)-4-phenylpiperidine as a colourless oil (298 mg, 0.964 mmol, 96%). Found (EI) 310.2167, $C_{21}H_{28}NO$ requires 310.2165; ν_{max} 2933, 1612, 1512, 1453, 1245, 1177, 1037, 822, 757 and 699 cm^{-1} ; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.15 - 7.35 (5 H, m, Ar*H*), 7.11 (2 H, d, *J*=8.1 Hz, Ar*H*), 6.83 (2 H, d, *J*=8.2 Hz, Ar*H*), 3.78 (3 H, s, OC*H*$_3$), 3.04 (2 H, d, *J*=11.0 Hz, *CH*$_2$N*CH*$_2$), 2.59 (2 H, t, *J*=7.6 Hz, N*CH*$_2$CH$_2$CH$_2$), 2.47 (1 H, tt, *J*=10.1, 5.5 Hz, Ph*CH*(CH$_2$)$_2$), 2.35 - 2.42 (2 H, m, *CH*$_2$), 1.97 - 2.09 (2 H, m, *CH*$_2$), 1.72 - 1.91 (6 H, m, *CH*$_2$) ppm; ^{13}C NMR (126 MHz, $CDCl_3$) δ 157.74, 146.49, 134.32, 129.29, 128.43, 126.90, 126.12, 113.75, 58.52, 55.27, 54.45, 42.83, 33.55, 33.00, 29.06 ppm; m/z (ESI) 310 ($M+H^+$, 100%).

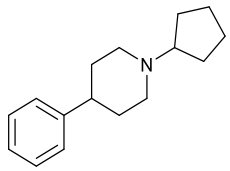
4-Phenyl-1-(6-(trimethylsilyl)hex-5-yn-1-yl)piperidine.



This compound is novel. 4-Phenyl-1-(6-(trimethylsilyl)hex-5-yn-1-yl)piperidine was synthesised via the general method from 4-phenylpiperidine (161 mg, 1.00 mmol) and 6-(trimethylsilyl)hex-5-yn-1-ol (332 mg, 2.00 mmol). Tricarbonyl(1,8-bis(trimethylsilyl)octa-1,7-diyne)iron (42.0 mg, 0.100 mmol) was used with trimethylamine N-oxide (15.0 mg, 0.2 mmol). Purification via column chromatography eluted with 0-60% ethyl acetate in pentane gave 4-phenyl-1-(6-

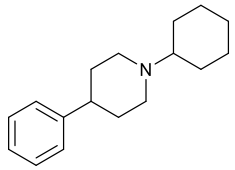
(trimethylsilyl)hex-5-yn-1-yl)piperidine as a colourless oil (232 mg, 0.741 mmol, 74%). Found (EI) 314.2297, $C_{20}H_{32}NSi$ requires 314.2299; ν_{max} 2935, 2864, 2802, 2765, 2173, 1452, 1249, 1130, 842, 758 and 716 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.15 - 7.34 (5 H, m, Ar*H*), 3.05 (2 H, d, *J*=11.6 Hz, N*CH*$_2$), 2.49 (1 H, tt, *J*= 11.1, 4.7 Hz, Ph*CH*), 2.35 - 2.41 (2 H, m, *CH*$_2$), 2.26 (2 H, t, *J*=7.0 Hz, N*CH*$_2$), 2.02 (td, *J*=11.2, 3.4 Hz, 2 H, *CH*$_2$N*CH*$_2$), 1.73 - 1.90 (m, 4 H, *CH*$_2$), 1.48 - 1.71 (m, 4 H, *CH*$_2$*CH*$_2$ in chain), 0.15 (s, 9 H, Si(*CH*$_3$)$_3$) ppm; ^{13}C NMR (126 MHz, $CDCl_3$) δ 146.28, 128.21, 126.68, 125.91, 107.15, 84.38, 58.36, 54.23, 42.64, 33.32, 26.61, 26.03, 19.66, -0.01 ppm; m/z (ESI) 314 (M+H, 100%).

1-Cyclopentyl-4-phenylpiperidine:



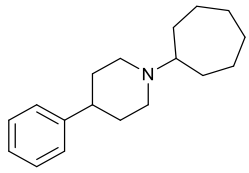
This compound is novel. 1-Cyclopentyl-4-phenylpiperidine was synthesised through the general procedure using 4-phenylpiperidine (161 mg, 1.00 mmol) and cyclopentanol (182 µL, 172 mg, 2.00 mmol). Tricarbonyl(1,8-bis(trimethylsilyl)octa-1,7-diyne)iron (42.0 mg, 0.100 mmol) was used with trimethylamine N-oxide (15.0 mg, 0.200 mmol). 1-Cyclohexyl-4-phenylpiperidine was isolated via column chromatography eluted with 0-60% ethyl acetate in pentane to give a colourless oil (207 mg, 0.904 mmol, 90%). Found (ESI) 230.1905, $C_{16}H_{24}N$ requires 230.1903; ν_{max} 2954, 2867, 2793, 2748, 1494, 1451, 1377, 1251, 1146, 756, 698 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$) δ ppm 6.95 - 7.65 (5 H, m, Ar*H*), 3.16 (2 H, d, *J*=11.8 Hz, CH*H*NCH*H*), 2.36 - 2.60 (2 H, m, C*H*HNC*H*H), 1.97 - 2.10 (2 H, m, C*H*$_2$), 1.76 - 1.96 (6 H, m, C*H*$_2$), 1.63 - 1.76 (2 H, m, C*H*$_2$), 1.51 - 1.63 (2 H, m, C*H*$_2$), 1.36 - 1.50 (2 H, m, C*H*$_2$); ^{13}C NMR (126 MHz, $CDCl_3$) δ ppm 146.50, 128.35, 126.85, 126.04, 67.78, 53.35, 42.82, 33.48, 30.62, 24.20; m/z 230 (M+H, 100%).

1-Cyclohexyl-4-phenylpiperidine:



This compound is novel. 1-Cyclohexyl-4-phenylpiperidine was synthesised via the general procedure using 4-phenylpiperidine (161 mg, 1.00 mmol) and cyclohexanol (210 µL, 200 mg, 2.00 mmol). Tricarbonyl(1,8-bis(trimethylsilyl)octa-1,7-diyne)iron (42.0 mg, 0.100 mmol) was used with trimethylamine N-oxide (15.0 mg, 0.200 mmol). 1-Cyclohexyl-4-phenylpiperidine was isolated via column chromatography eluted with 0-60% ethyl acetate in pentane to give a colourless oil (228 mg, 0.938 mmol, 94%). Found (ESI) 244.2060, $C_{17}H_{26}N$ requires 244.2060; ;ν_{max} 2928, 2798, 2739, 1494, 1451, 1377, 1290, 1152, 754, 697 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$) δ ppm 7.13 - 7.38 (5 H, m, Ar*H*), 3.03 (2 H, d, *J*=11.4 Hz, CH*H*NCH*H*), 2.47 (1 H, tt, *J*=12.0, 3.9 Hz, C*H*$(CH_2)_2$), 2.32 (3 H, td, *J*=11.5, 2.2 Hz, CH_2), 1.70 - 2.01 (8 H, m, CH_2), 1.64 (1 H, d, *J*=12.2 Hz, NC*H*), 1.19 - 1.33 (4 H, m, CH_2), 1.00 - 1.18 (1 H, m, CH*H*); ^{13}C NMR (126 MHz, $CDCl_3$) δ ppm 146.69, 128.38, 126.92, 126.03, 64.07, 49.89, 43.26, 34.05, 28.90, 26.47, 26.17; m/z 244 (M+H, 100%).

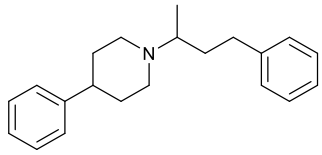
1-Cycloheptyl-4-phenylpiperidine:



This compound is novel. 1-Cycloheptyl-4-phenylpiperidine was synthesised via the general procedure using 1-phenylpiperidine (161 mg, 1.00 mmol) and cycloheptanol (240 µL, 228 mg, 2.00 mmol). Tricarbonyl(1,8-bis(trimethylsilyl)octa-1,7-diyne)iron (42.0 mg, 0.100 mmol) was used with trimethylamine N-oxide (15.0 mg, 0.200 mmol). 1-Cycloheptyl-4-phenylpiperidine was isolated via column chromatography eluted with 0-60% ethyl acetate in pentane to give a colourless oil (252 mg, 0.981 mmol, 98%). Found (ESI) 258.2216, $C_{18}H_{28}N$ requires 258.2216; ; ν_{max} 2926, 2868,

2796, 1494, 1450, 1377, 1251, 1151, 753, 698 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$) δ ppm 7.25 - 7.33 (2 H, m, Ar*H*), 7.20 - 7.25 (2 H, m, Ar*H*), 7.14 - 7.20 (1 H, m, Ar*H*), 2.89 (2 H, d, *J*=11.4 Hz, CH*H*NCH*H*), 2.55 - 2.66 (1 H, m, NC*H*), 2.45 (1 H, tt, *J*=11.9, 3.9 Hz, PhC*H*), 2.37 (2 H, td, *J*=11.6, 2.4 Hz, C*H*HNC*H*H), 1.63 - 1.95 (8 H, m) 1.34 - 1.63 (8 H, m); ^{13}C NMR (126 MHz, $CDCl_3$) δ ppm 146.72, 128.37, 126.92, 126.02, 65.42, 49.33, 43.31, 34.10, 29.92, 28.20, 26.03; m/z 258 (M+H, 100%).

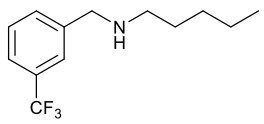
4-Phenyl-1-(4-phenylbutan-2-yl)piperidine:



This compound is novel. 4-Phenyl-1-(4-phenylbutan-2-yl)piperidine was synthesised through the general procedure using 4-phenylpiperidine (161mg, 1.00 mmol) and 4-phenylbutan-2-ol (309 µL, 300 mg, 2.00 mmol). Tricarbonyl(1,8-bis(trimethylsilyl)octa-1,7-diyne)iron (42.0 mg, 0.100 mmol) was used with trimethylamine N-oxide (15.0 mg, 0.200 mmol). 4-Phenyl-1-(4-phenylbutan-2-yl)piperidine was isolated via column chromatography eluted with 0-60% ethyl acetate in pentane to given a colourless oil (275 mg, 0.939 mmol, 94%). Found 294.2217, $C_{21}H_{28}N$ requires 294.2216; ν_{max} 2975, 2784, 1665, 1478, 1321, 1118, 1081, 1061, 994, 753, 697 and 555 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$) δ ppm 7.05 - 7.50 (10 H, m, Ar*H*), 2.90 (2 H, m), 2.57 - 2.78 (3 H, m), 2.47 (2 H, m), 2.29 (1 H, m), 1.66 - 2.05 (6 H, m), 1.53 - 1.66 (1 H, m), 1.06 (3 H, d, *J*=4.3 Hz, CHC*H*$_3$); ^{13}C NMR (126 MHz, $CDCl_3$) δ ppm 146.63, 142.74, 128.45, 128.35, 128.26, 126.88, 126.02, 125.62, 58.64, 51.05, 46.96, 43.22, 35.55, 33.22, 13.85; m/z 294 (M+H, 100%).

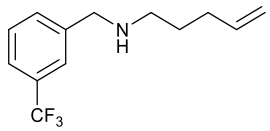
(3.5) Synthesis of Benzylamine-based Amines

N-(3-(trifluoromethyl)benzyl)pentan-1-amine:



This compound is known and has been fully characterised.[35] This compound is novel. *N*-(3-(Trifluoromethyl)benzyl)pentan-1-amine was synthesised via the general procedure using 3-(trifluoromethyl)benzylamine (147 µL, 175 mg, 1.00 mmol) and pentan-1-ol (217 µL, 176 mg, 2.00 mmol). Tricarbonyl(1,8-bis(trimethylsilyl)octa-1,7-diyne)iron (42.0 mg, 0.100 mmol) was used with trimethylamine N-oxide (15.0 mg, 0.2 mmol). The product was isolated using column chromatography eluted with 0-20% ethyl acetate in pentane to give *N*-(3-(trifluoromethyl)benzyl)pent-4-en-1-amine as a colourless oil (220 mg, 0.898 mmol, 90%). ^{1}H NMR (500 MHz, $CDCl_3$) δ ppm 7.60 (1 H, s, Ar*H*), 7.47 - 7.55 (2 H, m, Ar*H*), 7.39 - 7.46 (1 H, m, Ar*H*), 3.84 (2 H, s, ArCH_2NH), 2.62 (2 H, t, *J*=7.2 Hz, NHCH_2CH$_2$), 1.63 (1 H, br. s., N*H*), 1.52 (2 H, quin, *J*=7.2 Hz), 1.26 - 1.39 (4 H, m, CH_2CH_2), 0.85 - 0.94 (3 H, m, CH_3); ^{13}C NMR (126 MHz, $CDCl_3$) δ ppm 131.43, 130.67 (q, *J*=32.1 Hz), 128.75, 124.77 (q, *J*=4.0 Hz), 123.76 (q, *J*=3.0 Hz), 124.24 (q, *J*=272.0 Hz), 53.54, 49.51, 29.74, 29.50, 22.59, 14.01; m/z 246 (M+H, 100%).

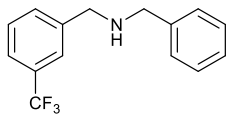
N-(3-(trifluoromethyl)benzyl)pent-4-en-1-amine.



This compound is novel. *N*-(3-(Trifluoromethyl)benzyl)pent-4-en-1-amine was synthesised via the general procedure using 3-(trifluoromethyl)benzylamine (147 µL, 175 mg, 1.00 mmol) and 4-penten-1-ol (208 µL, 172 mg, 2.00 mmol). Tricarbonyl(1,8-bis(trimethylsilyl)octa-1,7-diyne)iron (42.0 mg, 0.100 mmol) was used with trimethylamine N-oxide (15.0 mg, 0.2 mmol). The product was isolated using column chromatography eluted with 0-20% ethyl acetate in pentane to give

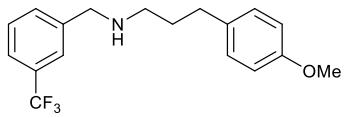
N-(3-(trifluoromethyl)benzyl)pent-4-en-1-amine as a colourless oil (196 mg, 0.807 mmol, 81%). Found (ESI) 244.1311, $C_{13}H_{17}F_3N$ requires 244.1308; ν_{max} 3302, 2930, 2855, 1679, 1641, 1451, 1329, 1164, 1125, 1073, 915, 798 and 702 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$) δ 7.59 (1 H, s, Ar*H*) 7.48 - 7.54 (2 H, m, Ar*H*) 7.40 - 7.46 (1 H, m, Ar*H*) 5.81 (1 H, ddt, *J*=17.1, 10.3, 6.7 Hz, *CH*=CH_2) 5.02 (1 H, dd, *J*=17.1, 1.7 Hz, CH=*CH₂*) 4.96 (1 H, d, *J*=10.1 Hz, CH=*CH₂*) 3.84 (2 H, s, Ar*CH₂*N) 2.65 (2 H, t, *J*=7.2 Hz, N*CH₂*CH_2) 2.11 (2 H, q, *J*=6.9 Hz, CH_2*CH₂*CH) 1.62 (2 H, quin, *J*=7.3 Hz, CH_2*CH₂*CH_2) 1.44 (1 H, br. s., *NH*) ppm; ^{13}C NMR (126 MHz, $CDCl_3$) δ 141.56, 138.39, 131.40, 130.68 (q, *J*=32.1 Hz,) 128.76, 124.75 (q, *J*=4.0 Hz), 123.74 (q, *J*=4.0 Hz), 124.24 (q, *J*=272.0 Hz), 114.74, 53.51, 48.90, 31.49, 29.20 ppm; m/z (ESI) 244 ($M+H^+$, 100%).

N-Benzyl-1-(3-(trifluoromethyl)phenyl)methanamine.



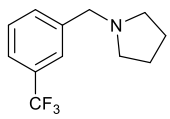
This compound is novel. *N*-Benzyl-1-(3-(trifluoromethyl)phenyl)methanamine was synthesised via the general reaction procedure using 3-(trifluoromethyl)benzylamine (143 µL, 175 mg, 1.00 mmol) and benzyl alcohol (310 µL, 324 mg, 3.00 mmol). Tricarbonyl(1,8-bis(trimethylsilyl)octa-1,7-diyne)iron (42.0 mg, 0.100 mmol) was used with trimethylamine N-oxide (15.0 mg, 0.2 mmol). *N*-Benzyl-1-(3-(trifluoromethyl)phenyl)methanamine was isolated through column chromatpgraphy eluted with 0-60% ethyl acetate in pentane to give a colourless oil (232 mg, 0.875 mmol, 88%). Found 266.1150, $C_{15}H_{15}F_3N$ requires 266.1151; ^1H NMR (500 MHz, $CDCl_3$) δ 7.62 (1 H, s, Ar*H*), 7.52 (2 H, m, Ar*H*), 7.40 - 7.46 (1 H, m, Ar*H*), 7.32 - 7.36 (4 H, m, Ar*H*), 7.24 - 7.29 (1 H, m, Ar*H*), 3.86 (2 H, s, NHC*H₂*), 3.81 (2 H, s, NH*CH₂*), 1.66 (1 H, br. s., N*H*) ppm; ^{13}C NMR (126 MHz, $CDCl_3$) δ 141.37, 140.01, 131.47, 130.71 (q, *J*=33.1 Hz), 128.79, 128.50, 128.16, 127.15, 124.84 (q, *J*=4.0 Hz), 123.82 (q, *J*=4.0 Hz), 124.25 (q, *J*=272.0 Hz), 53.26, 52.63 ppm; m/z 266 (M+H, 100%).

3-(4-Methoxyphenyl)-*N*-(3-(trifluoromethyl)benzyl)propan-1-amine.



This compound is novel. 3-(4-Methoxyphenyl)-*N*-(3-(trifluoromethyl)benzyl)propan-1-amine was synthesised via the general procedure using 3-(trifluoromethyl)benzylamine (147 µL, 175 mg, 1.00 mmol) and 3-(4-methoxyphenyl)-1-propanol (332 mg, 2.00 mmol). Tricarbonyl(1,8-bis(trimethylsilyl)octa-1,7-diyne)iron (42.0 mg, 0.100 mmol) was used with trimethylamine N-oxide (15.0 mg, 0.2 mmol). The product was isolated using column chromatography eluted with 0-30% ethyl acetate in pentane to give 3-(4-methoxyphenyl)-*N*-(3-(trifluoromethyl)benzyl)propan-1-amine as a colourless oil (295 mg, 0.913 mmol, 91%). Found (EI) 324.1575, $C_{18}H_{21}F_3NO$ requires 324.1570; ν_{max} 2932, 2833, 1611, 1511, 1453, 1300, 1243, 1176, 1112, 1034, 812, 733, 697, 558 and 520 cm^{-1} ; ^1H NMR (500 MHz, $CDCl_3$) δ 7.58 (1 H, s, Ar*H*) 7.46 - 7.53 (2 H, m, Ar*H*) 7.38 - 7.44 (1 H, m, Ar*H*) 7.08 (2 H, d, *J*=8.7 Hz, Ar*H*) 6.81 (2 H, d, *J*=8.7 Hz, Ar*H*) 3.81 (2 H, s, ArCH_2NH) 3.76 (3 H, s, O*Me*) 2.64 (2 H, t, *J*=7.1 Hz, NHCH_2CH_2) 2.61 (2 H, t, *J*=7.7 Hz, ArCH_2CH_2) 1.80 (2 H, quin, *J*=7.3 Hz, $CH_2CH_2CH_2$) ppm; ^{13}C NMR (126 MHz, $CDCL_3$) δ 157.80, 141.60, 134.12, 131.47, 130.67 (q, *J*=32.1 Hz), 129.26, 128.78, 124.78 (q, *J*=4.0 Hz), 123.75 (q, *J*=4.0 Hz), 124.29 (q, *J*=272.0 Hz), 113.79, 55.23, 53.53, 48.91, 32.67, 31.90 ppm; m/z (ESI) 324 ($M+H^+$, 100%).

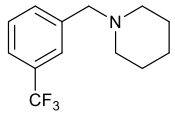
1-(3-(Trifluoromethyl)benzyl)pyrrolidine.



This compound is known and has been fully characterised.[54] 1-(3-(Trifluoromethyl)benzyl)pyrrolidine was synthesised via the general procedure using 3-(trifluoromethyl)benzylamine (143 µL, 175 mg, 1.00 mmol) and 1,4-butanediol (177 µL, 180 mg, 2.00 mmol). Tricarbonyl(1,8-bis(trimethylsilyl)octa-1,7-diyne)iron (42.0 mg, 0.100 mmol) was used with trimethylamine N-oxide (15.0 mg,

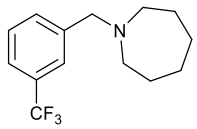
0.2 mmol). The product was isolated via column chromatography eluted with 0-60% ethyl acetate in pentane to give 1-(3-(Trifluoromethyl)benzyl)pyrrolidine as a colourless oil (188 mg, 0.821 mmol, 82%). ^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 7.60 (1 H, s, Ar*H*), 7.51 (2 H, t, *J*=9.2 Hz, Ar*H*), 7.42 (1 H, t, *J*=7.8 Hz, Ar*H*), 3.66 (2 H, s, ArC*H*$_2$), 2.42 - 2.61 (4 H, m, C*H*$_2$), 1.80 (4 H, dt, *J*=6.8, 3.3 Hz, C*H*$_2$C*H*$_2$); m/z (ESI) 230 (M+H, 100%).

1-(3-(Trifluoromethyl)benzyl)piperidine.



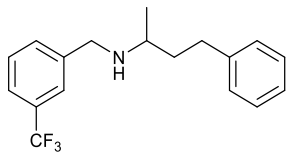
This compound is known, but not fully characterised.[54] 1-(3-(Trifluoromethyl)benzyl)piperidine was synthesised via the general procedure using 3-(trifluoromethyl)benzylamine (143 µL, 175 mg, 1.00 mmol) and 1,5-pentanediol (104 mg, 2.00 mmol). Tricarbonyl(1,8-bis(trimethylsilyl)octa-1,7-diyne)iron (42.0 mg, 0.100 mmol) was used with trimethylamine N-oxide (15.0 mg, 0.2 mmol). The product was isolated via column chromatography eluted with 0-60% ethyl acetate in pentane to give 1-(3-(Trifluoromethyl)benzyl)piperidine as a colourless oil (226 mg, 0.930 mmol, 93%). Found (EI) 244.1312, $C_{13}H_{17}F_3N$ requires 244.1308; ν_{max} 2936, 2855, 2798, 2758, 1445, 1325, 1162, 1121, 1071, 780 and 702 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.58 (1 H, s, *ArH*) 7.46 - 7.54 (2 H, m, *ArH*) 7.35 - 7.45 (1 H, m, *ArH*) 3.50 (2 H, s, Ph*CH*$_2$N) 2.37 (4 H, m, N*CH*$_2$) 1.58 (4 H, quin, *J*=5.6 Hz, NCH$_2$*CH*$_2$) 1.35 - 1.51 (2 H, m, *CH*$_2$) ppm; ^{13}C NMR (126 MHz, $CDCl_3$) δ 139.92, 132.54, 130.45 (q, *J*=32.1 Hz), 128.53, 125.76 (q, *J*=4.0 Hz), 123.77 (q, *J*=4.0 Hz), 124.43 (q, *J*=272.0 Hz), 63.29, 54.52, 25.95, 24.30 ppm; m/z (ESI) 244 (M+H, 100%).

1-(3-(Trifluoromethyl)benzyl)azepane:



This compound is known and has been fully characterised.[35] 1-(3-(Trifluoromethyl)benzyl)azepane was synthesised through the general procedure using 3-(trifluoromethyl)benzylamine (143 µL, 175 mg, 1.00 mmol) and 1,6-hexanediol (236 mg, 2.00 mmol). Tricarbonyl(1,8-bis(trimethylsilyl)octa-1,7-diyne)iron (42.0 mg, 0.100 mmol) was used with trimethylamine N-oxide (15.0 mg, 0.200 mmol). 1-(3-(trifluoromethyl)benzyl)azepane was isolated via column chromatography eluted with 0-60% ethyl acetate in pentane to give a colourless oil (224 mg, 0.872 mmol, 87%). Found (ESI) 258.1465, $C_{14}H_{19}F_3N$ requires 258.1464; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.62 (1 H, s, Ar*H*), 7.53 (1 H, d, *J*=7.6 Hz, Ar*H*), 7.48 (1 H, d, *J*=7.6 Hz, Ar*H*), 7.40 (1 H, t, *J*=7.6 Hz, Ar*H*), 3.67 (2 H, s, ArC*H*$_2$N), 2.61 (4 H, m, C*H*$_2$NC*H*$_2$ in ring), 1.62 (8 H, m, C*H*$_2$C*H*$_2$C*H*$_2$C*H*$_2$ in ring) ppm; ^{13}C NMR (126 MHz, $CDCl_3$) δ 141.37, 131.90, 130.44 (q, *J*=32.1 Hz), 128.48, 125.25 (q, *J*=4.0 Hz), 123.52 (q, *J*=4.0 Hz), 124.33 (q, *J*=272.0 Hz), 62.23, 55.61, 28.29, 26.98 ppm; m/z (ESI) 258 (M+H, 100%).

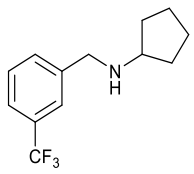
4-Phenyl-*N*-(3-(trifluoromethyl)benzyl)butan-2-amine:



This compound is novel. 4-Phenyl-*N*-(3-(trifluoromethyl)benzyl)butan-2-amine was synthesised following the general procedure using 3-(trifluoromethyl)benzylamine (148 µL, 175 mg, 1.00 mmol) and 4-phenylbutan-2-ol (309 µL, 300 mg, 2.00 mmol). Tricarbonyl(1,8-bis(trimethylsilyl)octa-1,7-diyne)iron (42.0 mg, 0.100 mmol) was used with trimethylamine N-oxide (15.0 mg, 0.2 mmol). 4-Phenyl-*N*-(3-(trifluoromethyl)benzyl)butan-2-amine was isolated through column chromatography eluted with 0-60% ethyl acetate in pentane to give a colourless oil

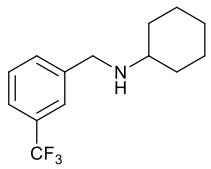
(270 mg, 0.879 mmol, 88%). Found (ESI) 308.1621, $C_{18}H_{21}F_3N$ requires 308.1621; ; ν_{max} 2967, 2942, 2921, 2901, 1646, 1599, 1495, 1452, 1377, 1329, 1298, 1165, 1124, 1077, 701; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.59 (1 H, s, Ar*H*), 7.49 (2 H, d, *J*=7.8 Hz, Ar*H*), 7.36 - 7.45 (1 H, m, Ar*H*), 7.22 - 7.31 (2 H, m, Ar*H*), 7.17 (3 H, m, Ar*H*), 3.87 (1 H, ab, *J*=13.6 Hz), 3.78 (1 H, ab, *J*=13.4 Hz), 2.59 - 2.78 (3 H, m, C*H* + C*H*$_2$) 1.81 (1 H, ddt, *J*=13.5, 9.3, 6.6 Hz, CH*H*) 1.68 (1 H, ddt, *J*=13.5, 9.3, 6.6 Hz, C*H*H) 1.28 (1 H, br. s., N*H*) 1.15 (3 H, d, *J*=6.3 Hz, CHC*H*$_3$) ppm; ^{13}C NMR (126 MHz, $CDCl_3$) δ 142.36, 141.96, 131.50, 130.67 (q, *J*=32.10 Hz), 128.39, 128.35, 125.79, 124.81 (q, *J*=4.00 Hz), 123.71 (q, *J*=4.0 Hz), 124.27 (q, *J*=272.0 Hz), 52.23, 50.81, 38.73, 32.32, 20.45 ppm; m/z 308 (M+H, 100%).

N-(3-(trifluoromethyl)benzyl)cyclopentanamine:



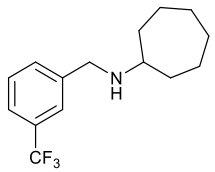
This compound is novel. *N*-(3-(trifluoromethyl)benzyl)cyclopentanamine was synthesised via the general procedure using 3-(trifluoromethyl)benzylamine (143 µL, 175 mg, 1.00 mmol) and cyclopentanol (182 µL, 172 mg, 2.00 mmol). Tricarbonyl(1,8-bis(trimethylsilyl)octa-1,7-diyne)iron (42.0 mg, 0.100 mmol) was used with trimethylamine N-oxide (15.0 mg, 0.200 mmol). *N*-(3-(trifluoromethyl)benzyl)cyclopentanamine was isolated through the use of column chromatography eluted with 0-60% ethyl acetate in pentane to give a colourless oil (233mg, 0.959 mmol, 96%). Found (ESI) 244.1305, $C_{13}H_{17}F_3N$ requires 244.1308; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.60 (1 H, s, Ar*H*), 7.46 - 7.55 (2 H, m, Ar*H*), 7.36 - 7.45 (1 H, m, Ar*H*), 3.82 (2 H, s, ArC*H*$_2$), 3.11 (1 H, quin, *J*=6.6 Hz, NC*H*), 1.78 - 1.95 (2 H, m), 1.70 (2 H, m), 1.46 - 1.62 (2 H, m), 1.27 - 1.45 (2 H, m) ppm; ^{13}C NMR (126 MHz, $CDCl_3$) δ 141.86, 131.49, 130.64 (q, *J*=31.1 Hz), 128.69, 124.78 (q, *J*=3.5 Hz), 123.65 (q, *J*=3.0 Hz), 124.26 (q, *J*=272.1 Hz), 59.40, 52.27, 33.18, 24.04 ppm; m/z 244 (M+H, 100%).

N-(3-(trifluoromethyl)benzyl)cyclohexanamine:



This compound is novel. *N*-(3-(trifluoromethyl)benzyl)cyclohexanamine was synthesised through the general procedure using 3-(trifluoromethyl)benzylamine (143 µL, 175 mg, 1.00 mmol) and cyclohexanol (210 µL, 200 mg, 2.00 mmol). Tricarbonyl(1,8-bis(trimethylsilyl)octa-1,7-diyne)iron (42.0 mg, 0.100 mmol) was used with trimethylamine N-oxide (15.0 mg, 0.200 mmol). *N*-(3-(trifluoromethyl)benzyl)cyclohexanamine was isolated through the use of column chromatography eluted with 0-60% ethyl acetate in pentane to give a colourless oil (249 mg, 0.969 mmol, 97%). Found (ESI) 258.1463, $C_{14}H_{19}F_3N$ requires 258.1464; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.60 (1 H, s, Ar*H*), 7.50 (2 H, m, Ar*H*), 7.41 (1 H, m, Ar*H*), 3.86 (2 H, s, ArC*H*$_2$NH), 2.48 (1 H, tt, *J*=10.2, 3.7 Hz, NHC*H*), 1.87 - 1.99 (2 H, m, C*H*$_2$), 1.69 - 1.82 (2 H, m, C*H*$_2$), 1.56 - 1.66 (1 H, m, C*H*H), 1.03 - 1.39 (5 H, m, C*H*$_2$) ppm; ^{13}C NMR (126 MHz, $CDCl_3$) δ 131.35, 130.61 (q, *J*=32.1 Hz), 128.70, 124.69 (q, *J*=3.0 Hz), 123.58 (q, *J*=4.0 Hz), 124.22 (q, *J*=273.1 Hz), 56.35, 50.55, 33.56, 26.11, 24.95 ppm; m/z (ESI) 258 (M+H, 100%).

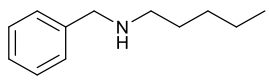
N-(3-(trifluoromethyl)benzyl)cycloheptanamine:



This compound is novel. *N*-(3-(trifluoromethyl)benzyl)cycloheptanamine was synthesised following the general procedure using 3-(trifluoromethyl)benzylamine (143 µL, 175 mg, 1.00 mmol) and cycloheptanol (240 µL, 228 mg, 2.00 mmol). Tricarbonyl(1,8-bis(trimethylsilyl)octa-1,7-diyne)iron (42.0 mg, 0.100 mmol) was used with trimethylamine N-oxide (15.0 mg, 0.200 mmol). *N*-(3-(trifluoromethyl)benzyl)cycloheptanamine was isolated through column

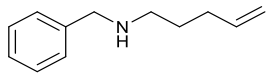
chromatography eluted with 0-60% ethyl acetate in pentane to give a colourless oil (255mg, 0.941 mmol, 94%). Found (ESI) 272.1622, $C_{15}H_{21}F_3N$ requires 272.1621; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.59 (1 H, s, Ar*H*), 7.50 (2 H, t, *J*=9.0 Hz, Ar*H*), 7.42 (1 H, t, *J*=7.6 Hz, Ar*H*), 3.83 (1 H, s, ArCH_2), 2.68 (1 H, tt, *J*=8.5, 4.1 Hz), 1.79 - 1.93 (2 H, m, C*H*HCHC*H*H), 1.61 - 1.75 (2 H, m, CH*H*CHCH*H*), 1.48 - 1.61 (4 H, m, CH_2 + CH_2), 1.36 - 1.48 (4 H, m, CH_2CH_2) ppm; ^{13}C NMR (126 MHz, $CDCl_3$) δ 142.03, 131.39, 130.61 (q, *J*=31.1 Hz), 128.70, 124.72 (q, *J*=4.0 Hz), 123.59 (q, *J*=4.0 Hz), 124.22 (q, *J*=272.1 Hz), 58.47, 51.11, 34.82, 28.33, 24.27 ppm; m/z 272 (M+H, 100%).

N-Benzylpentan-1-amine



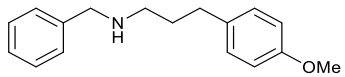
This compound is known, but not fully characterised.[36] *N*-Benzylpentan-1-amine was synthesised via the general procedure using benzylamine (109 µL, 107 mg, 1.00 mmol) and 1-pentanol (217 µL, 172 mg, 2.00 mmol). Tricarbonyl(1,8-bis(trimethylsilyl)octa-1,7-diyne)iron (42.0 mg, 0.100 mmol) was used with trimethylamine N-oxide (15.0 mg, 0.200 mmol). The product was isolated using column chromatography eluted with 0-20% ethyl acetate in pentane to give *N*-Benzylpentan-1-amine as a colourless oil (92 mg, 0.518 mmol, 52%). Found (ESI) 178.1590, $C_{12}H_{20}N$ requires 178.1590; ν_{max} 3310, 2928, 2857, 2797, 1657, 1495, 1453, 1377, 1120, 1028, 734 and 697 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.06 - 7.45 (5 H, m, Ar*H*) 3.79 (2 H, s, PhCH_2) 2.63 (2 H, t, *J*=7.3 Hz, NCH_2CH$_2$) 1.64 (1 H, br. s., N*H*) 1.43 - 1.60 (2 H, m, CH_2) 1.31 (4 H, m, CH_2) 0.89 (3 H, t, *J*=6.5 Hz, CH$_2$CH_3) ppm; ^{13}C NMR (126 MHz, $CDCl_3$) δ 140.22, 128.41, 128.20, 126.95, 54.00, 49.41, 29.67, 29.55, 22.62, 14.06 ppm; m/z (ESI) 178 (M+H, 100%).

N-Benzylpent-4-en-1-amine,



This compound is novel. *N*-Benzylpent-4-en-1-amine was synthesised via the general procedure using benzylamine (109 µL, 107 mg, 1.00 mmol) and 4-penten-1-ol (208 µL, 172 mg, 2.00 mmol). Tricarbonyl(1,8-bis(trimethylsilyl)octa-1,7-diyne)iron (42.0 mg, 0.100 mmol) was used with trimethylamine N-oxide (15.0 mg, 0.2 mmol). The product was isolated using column chromatography eluted with 0-100% ethyl acetate in pentane to give *N*-benzylpent-4-en-1-amine as a colourless oil (158 mg, 0.903 mmol, 90%). Found (ESI) 176.1433, $C_{12}H_{18}N$ requires 176.1434; ν_{max} 3076, 3064, 2928, 2814, 1640, 1494, 1453, 1266, 1118, 993, 910, 732 and 696 cm^{-1} ; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.28 - 7.38 (4 H, m, *ArH*) 7.20 - 7.28 (1 H, m, *ArH*) 5.81 (1 H, ddt, *J*=17.0, 10.2, 6.7 Hz, *CH*=CH_2) 4.90 - 5.05 (1 H, m, *CH_2*) 3.78 (2 H, s, Ph*CH_2*) 2.65 (2 H, t, *J*=7.2 Hz, $NHCH_2CH_2$*CH_2*) 2.10 (2 H, q, *J*=7.0 Hz, C*H_2*$CH=CH_2$) 1.61 (2 H, quin, *J*=7.4 Hz, $NHCH_2$*CH_2*CH_2) 1.47 (1 H, br. s., *NH*) ppm; ^{13}C NMR (126 MHz, $CDCl_3$) δ 140.49, 138.49, 128.36, 128.08, 126.86, 114.61, 54.03, 48.89, 31.54, 29.24 ppm; m/z 176 (M+H, 100%).

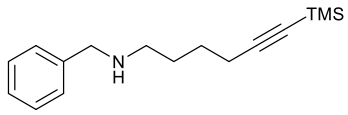
N-Benzyl-3-(4-methoxyphenyl)propan-1-amine.



This compound is novel. *N*-Benzyl-3-(4-methoxyphenyl)propan-1-amine was synthesised via the general procedure using benzylamine (107 mg, 1.00 mmol) and 3-(4-methoxyphenyl)-1-propanol (332 mg, 2.00 mmol). Tricarbonyl(1,8-bis(trimethylsilyl)octa-1,7-diyne)iron (42.0 mg, 0.100 mmol) was used with trimethylamine N-oxide (15.0 mg, 0.2 mmol). The product was isolated via column chromatography eluted with 0-60% ethyl acetate in pentane to give *N*-benzyl-3-(4-methoxyphenyl)propan-1-amine as a colourless oil (129 mg, 0.506 mmol, 51%). Found (EI) 256.1701, $C_{17}H_{22}NO$ requires 256.1696; ν_{max} 3061, 3028, 3002, 2932, 2833, 1611, 1511, 1453, 1243, 1176, 1034, 812, 733 and 697 cm^{-1}; ^{1}H NMR (500

MHz, $CDCl_3$) δ 7.28 - 7.35 (4 H, m, Ar*H*) 7.22 - 7.27 (1 H, m, Ar*H*) 7.09 (2 H, d, *J*=8.5 Hz, Ar*H*) 6.82 (2 H, d, *J*=8.7 Hz, Ar*H*) 3.74 - 3.82 (5 H, m, O*Me* + Ph*CH*$_2$) 2.66 (2 H, t, *J*=7.1 Hz, NH*CH*$_2$) 2.60 (2 H, t, *J*=7.7 Hz, Ar*CH*$_2$CH$_2$) 1.81 (2 H, quin, *J*=7.4 Hz, CH$_2$*CH*$_2$CH$_2$)1.49 (1 H, br. s, *NH)* ppm; ^{13}C NMR (126 MHz, $CDCl_3$) δ 157.70, 140.50, 134.25, 129.23, 128.37, 128.10, 126.87, 113.72, 55.23, 54.06, 48.87, 32.77, 31.83 ppm; m/z (ESI) 256 (M+H, 100%).

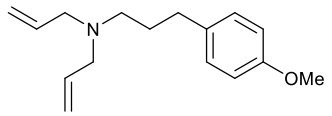
N-Benzyl-6-(trimethylsilyl)hex-5-yn-1-amine.



This compound is novel. *N*-Benzyl-6-(trimethylsilyl)hex-5-yn-1-amine was synthesised via the general procedure using benzylamine (107 mg, 1.00 mmol) and 6-(trimethylsilyl)hex-5-yn-1-ol (332 mg, 2.00 mmol). Tricarbonyl(1,8-bis(trimethylsilyl)octa-1,7-diyne)iron (42.0 mg, 0.100 mmol) was used with trimethylamine N-oxide (15.0 mg, 0.2 mmol). The product was isolated via column chromatography eluted with 0-60% ethyl acetate in pentane to give *N*-benzyl-6-(trimethylsilyl)hex-5-yn-1-amine as a colourless oil (51.0 mg, 0.197 mmol, 20%). Found (EI) 260.1829, $C_{16}H_{26}NSi$ requires 260.1829; ν_{max} 3301, 2955, 2935, 2172, 1454, 1249, 841, 759 and 698 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.22 - 7.31 (4 H, m, Ar*H*) 7.11 - 7.22 (1 H, m, Ar*H*) 3.72 (2 H, s, Ph*CH*$_2$NH) 2.58 (2 H, t, *J*=6.9 Hz, NH*CH*$_2$CH$_2$) 2.17 (2 H, t, *J*=6.9 Hz, *CH*$_2$CCTMS) 1.45 - 1.59 (4 H, m, CH$_2$*CH*$_2$*CH*$_2$CH$_2$) 1.41 (1 H, br. s., *NH*) 0.07 (9 H, s, CCSi(*CH*$_3$)$_3$ ppm; ^{13}C NMR (126 MHz, $CDCl_3$) δ 140.41, 128.37, 128.08, 126.87, 107.24, 84.55, 53.95, 48.84, 29.16, 26.39, 19.77, 0.14 ppm; m/z (ESI) 260 (M+H, 100%).

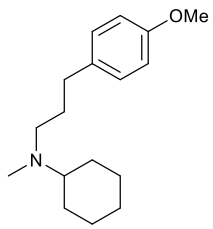
(3.6) Other Amines

N-allyl-*N*-(3-(4-Methoxyphenyl)propyl)prop-2-en-1-amine.



This compound is novel. *N*-allyl-*N*-(3-(4-methoxyphenyl)propyl)prop-2-en-1-amine was synthesised via the general procedure using diallylamine (123 µL, 97 mg, 1.00 mmol) and 3-(4-methoxyphenyl)-1-propanol (332 mg, 2.00 mmol). Tricarbonyl(1,8-bis(trimethylsilyl)octa-1,7-diyne)iron (42.0 mg, 0.100 mmol) was used with trimethylamine N-oxide (15.0 mg, 0.2 mmol). The product was isolated using column chromatography eluted with 0-20% ethyl acetate in pentane to give *N*-allyl-*N*-(3-(4-methoxyphenyl)propyl)prop-2-en-1-amine as a colourless oil (228 mg, 0.931 mmol, 93%). Found (EI) 246.1852, $C_{16}H_{24}NO$ requires 246.1852; ν_{max} 2945, 2866, 1636, 1524, 1416, 1301, 1111, 987, 755, 612 and 519 cm^{-1} ; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.09 (2 H, d, *J*=8.5 Hz, Ar*H*) 6.82 (2 H, d, *J*=8.5 Hz, Ar*H*) 5.85 (2 H, ddt, *J*=17.0, 10.3, 6.5 Hz, CH_2CH=CH_2) 5.09 - 5.19 (4 H, m, CH=CH_2) 3.78 (3 H, s, O*Me*) 3.08 (2 H, d, *J*=6.4 Hz, NCH_2CH=CH_2) 2.54 (2 H, t, *J*=7.8 Hz, N$CH_2CH_2CH_2$) 2.46 (2 H, t, *J*= 7.8 Hz, CH_2CH=CH_2) 1.75 (2 H, quin, *J*=7.7 Hz, $CH_2CH_2CH_2$) ppm; ^{13}C NMR (126 MHz, $CDCl_3$) δ 157.68, 135.79, 134.50, 129.24, 117.31, 113.70, 56.82, 55.27, 52.85, 32.77, 28.97 ppm; m/z (ESI) 246 ($M+H^+$, 100%).

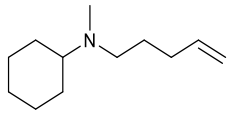
N-(3-(4-Methoxyphenyl)propyl-*N*-methylcyclohexanamine



This compound is novel. *N*-(3-(4-Methoxyphenyl)propyl-*N*-methylcyclohexanamine was synthesised via the general procedure using N-methylcyclohexylamine (130 µL, 113 mg, 1.00 mmol) and 3-(4-methoxyphenyl)-1-propanol (332 mg, 2.00 mmol).

Tricarbonyl(1,8-bis(trimethylsilyl)octa-1,7-diyne)iron (42.0 mg, 0.100 mmol) was used with trimethylamine N-oxide (15.0 mg, 0.2 mmol). The product was isolated using column chromatography eluted with 0-20% ethyl acetate in pentane to give *N*-(3-(4-Methoxyphenyl)propyl-*N*-methylcyclohexanamine as a colourless oil (235 mg, 0.893 mmol, 89%). Found (EI) 262.2169, $C_{17}H_{28}NO$ requires 262.2165; ν_{max} 2935, 2855, 1420, 1309, 1119, 979, 755, 617 and 527 cm^{-1} ; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.10 (2 H, d, *J*=8.5 Hz, Ar*H*) 6.82 (2 H, d, *J*=8.5 Hz, Ar*H*) 3.78 (3 H, s, O*Me*) 2.55 (2 H, t, *J*=7.8 Hz, NCH_2) 2.45 (2 H, t, *J*=7.5 Hz, ArCH_2) 2.30 - 2.40 (1 H, m, N*CH*) 2.24 (3 H, s, NCH_3) 1.69 - 1.84 (6 H, m, CH_2) 1.61 (1 H, d, *J*=12.5 Hz, *CH*) 1.13 - 1.27 (4 H, m, CH_2) 1.01 - 1.12 (1 H, m, *CH*) ppm; ^{13}C NMR (126 MHz, $CDCl_3$) δ 157.66, 134.55, 129.24, 113.69, 62.54, 55.24, 53.17, 37.74, 32.88, 29.90, 28.59, 26.42, 26.09 ppm; m/z (ESI) 262 ($M+H^+$, 100%).

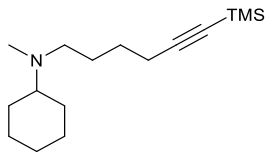
N-Methyl-*N*-(pent-4-en-1-yl)cyclohexanamine,



This compound is novel. *N*-Methyl-*N*-(pent-4-en-1-yl)cyclohexanamine was synthesised from *N*-methylcyclohexylamine (130 µL, 113 mg, 1.00 mmol) and 4-penten-1-ol (208 µL, 172 mg, 2.00 mmol). Tricarbonyl(1,8-bis(trimethylsilyl)octa-1,7-diyne)iron (42.0 mg, 0.100 mmol) was used with trimethylamine N-oxide (15.0 mg, 0.2 mmol). Purification of compound was via column chromatography eluted with 0-40% ethyl acetate in pentane to give *N*-methylcyclohexylamine as a colourless oil (163 mg, 0.884 mmol, 88%). Found (ESI) 182.1905, $C_{12}H_{24}N$ requires 182.1903; ν_{max} 2926, 2853, 2789, 1640, 1450, 1297, 1050, 991 and 908 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$) δ 5.83 (1 H, ddt, *J*=17.0, 10.3, 6.6 Hz, *CH*=CH_2) 5.02 (1 H, dd, *J*=17.1, 1.9 Hz, CH_2=CH) 4.95 (1 H, d, *J*=10.1 Hz, CH_2=CH) 2.40 - 2.46 (2 H, m,) 2.31 - 2.39 (1 H, m, N*CH*) 2.24 (3 H, s, NCH_3) 2.05 (2 H, q, *J*=6.9 Hz, $CH_2CH_2CH_2$ in chain) 1.78 (4 H, d, *J*=9.5 Hz, CH_2 in ring) 1.62 (1 H, d, *J*=12.7 Hz, *CH*) 1.55 (2 H, quin, *J*=7.6 Hz, $CH_2CH_2CH_2$ in chain) 1.14 - 1.28 (4 H, m, CH_2) 1.09 (1 H, td, *J*=12.9, 3.4 Hz, Ph*CH*)

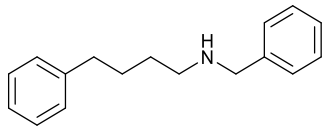
ppm; ^{13}C NMR (126 MHz, $CDCl_3$) δ 138.80, 114.41, 62.64, 53.15, 37.89, 31.75, 28.62, 27.22, 26.42, 26.07 ppm; m/z (ESI) 182 (M+H, 100%).

N-Methyl-*N*-(6-trimethylsilyl)hex-5-yn-1-yl)cyclohexanamine.



This compound is novel. *N*-Methyl-*N*-(6-trimethylsilyl)hex-5-yn-1-yl)cyclohexanamine was synthesised via the general procedure using *N*-methylcyclohexylamine (112 mg, 1.00 mmol) and 6-(trimethylsilyl)hex-5-yn-1-ol (332 mg, 2.00 mmol). Tricarbonyl(1,8-bis(trimethylsilyl)octa-1,7-diyne)iron (42.0 mg, 0.100 mmol) was used with trimethylamine N-oxide (15.0 mg, 0.2 mmol). The product was isolated via column chromatography eluted with 0-60% ethyl acetate in pentane to give (name) as a colourless oil (243 mg, 0.931 mmol, 93%). Found (ESI) 266.2305, $C_{16}H_{32}NSi$ requires 266.2299; ν_{max} 2929, 2855, 2791, 2174, 1451, 1328, 1248, 1128, 1048, 839, 759, 759, 699 and 640 cm^{-1} ; ^{1}H NMR (500 MHz, $CDCl_3$) δ 2.42 (t, *J*=6.9 Hz, 2 H, N*CH*$_2$) 2.28 - 2.38 (m, 1 H, N*CH*) 2.15 - 2.28 (m, 5 H, C*H*$_3$ + C*H*$_2$) 1.77 (d, *J*=9.3 Hz, 4 H, *CH*$_2$ in ring) 1.43 - 1.67 (m, 5 H, *CH*$_2$) 1.12 - 1.30 (m, 4 H, *CH*$_2$) 0.96 - 1.11 (m, 1 H, CH*H*) 0.12 (s, 9 H, Si(*CH*$_3$)$_3$) ppm; ^{13}C NMR (126 MHz, $CDCl_3$) δ 107.38, 84.42, 62.43, 53.01, 37.76, 28.54, 26.93, 26.53, 26.37, 26.02, 19.74, 0.13 ppm; m/z (ESI) 262 (M+H, 100%).

N-Benzyl-4-phenylbutan-1-amine

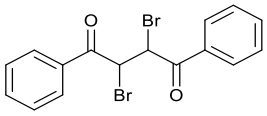


This compound is novel. *N*-Benzyl-4-phenylbutan-1-amine was synthesised from 4-phenylbutylamine (149 mg, 1.00 mmol) and benzyl alcohol (310 μL, 324 mg, 3.00 mmol). Tricarbonyl(1,8-bis(trimethylsilyl)octa-1,7-diyne)iron (42.0 mg, 0.100 mmol)

was used with trimethylamine N-oxide (15.0 mg, 0.2 mmol). The product was isolated via column chromatography eluted with 0-100% ethyl acetate in pentane to give *N*-benzyl-4-phenylbutan-1-amine as a colourless oil (110 mg, 0.460 mmol, 46%). Found (ESI) 240.1747, $C_{17}H_{22}N$ requires 240.1747; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.07 - 7.46 (10 H, m, Ar*H*) 3.77 (2 H, s, Ph*CH*$_2$) 2.51 - 2.83 (4 H, m, *CH*$_2$CH$_2$CH$_2$*CH*$_2$) 1.50 - 1.74 (4 H, m, CH$_2$*CH*$_2$*CH*$_2$CH$_2$) 1.44 (1 H, br. s., *NH*) ppm; ^{13}C NMR (126 MHz, $CDCl_3$) δ 142.51, 140.54, 128.43, 128.41, 128.30, 128.14, 126.91, 125.71, 54.12, 49.33, 35.86, 29.79, 29.23 ppm; m/z (ESI) 240 (M+H, 100%).

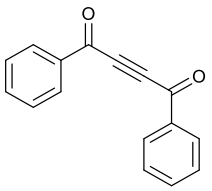
(3.7) Other Compounds

2,3-Dibromo-1,4-diphenylbutane-1,4-dione:---



This compound is known and has been full characterised.[41] Trans-dibenzoylethylene (1.18g, 5.00 mmol) was added to AcOH (20.0 mL) and was dissolved by stirring an dheating 50 ^{0}C. Br_2 (256 µL, 0.799g, 5.00 mmol) was added dropwise and the reaction was stirred at room temperature for 1 hour. The reaction was cooled to 0 ^{0}C and the product was collected via Buchner filtration to give a cream-coloured solid (1.40g, 3.54 mmol, 70%). ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.12 (4 H, d, *J*=7.6 Hz, Ar*H*), 7.67 (2 H, t, *J*=7.5 Hz, Ar*H*), 7.56 (4 H, t, *J*=7.6 Hz, Ar*H*), 5.97 (2 H, s, C*H*Br) ppm; ^{13}C NMR (101 MHz, $CDCl_3$) δ 190.60, 134.43, 133.99, 129.05, 41.18 ppm; m/z 419 (100%, M+Na).

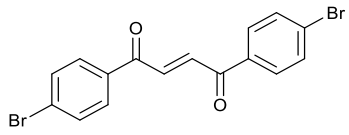
1,4-Diphenylbut-2-yne-1,4-dione:



This compound is known and has been fully characterised.[41] 2,3-Dibromo-1,4-diphenylbutane-1,4-dione (1.25g, 3.16 mmol) was added to acetone (12.0 mL) and

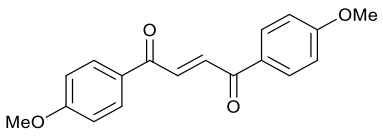
triethylamine (0.95 mL, 13.0 mmol) was added in a 100 mL round-bottom flask equipped with a Findenser. The reaction was refluxed with stirring for 1.5 hours to give a dark brown solution, which was cooled to room temperature and the precipitate was removed filtration. The solvent was removed by rotary evaporator to give a dark brown residue. The product was isolated via column chromatography eluted with 0-40 ethyl acetate in hexane to give a light-coloured solid (0.636g, 2.72 mmol, 86%). ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.19 (4 H, d, *J*=7.3 Hz, Ar*H*), 7.69 (2 H, t, *J*=7.3 Hz, Ar*H*), 7.55 (4 H, t, *J*=7.8 Hz, Ar*H*) ppm; ^{13}C NMR (126 MHz, $CDCl_3$) δ 176.58, 135.82, 135.19, 129.82, 129.00, 85.87 ppm; m/z 257 (100%, M+Na).

(*E*)-1,4-bis(4-bromophenyl)but-2-ene-1,4-dione:



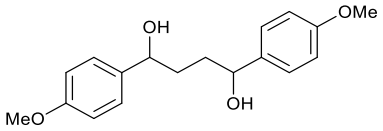
This compound is known and has been fully characterised.[39] 4'-methoxyacetophenone (0.398g, 1.00 mmol), $CuBr_2$ (0.0900g, 0.400 mmol), I_2 (1.016g, 4.00 mmol) and DMF (2.00 mL) were placed in a 15 mL ACE pressure tube and heated to 80 ^{0}C overnight with stirring. The reaction was worked up by addition of saturated $Na_2S_2O_4$ solution and extracted with ethyl acetate (3x20 mL). The solution was dried over anhydrous Na_2SO_4, filtered and solvent removed to give a yellow solid. Product was isolated via column chromatography eluted with 0-40% ethyl acetate in hexane to give a yellow solid (0.212g, 0.268 mmol, 54%). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.97 (2 H, s, C*H*C*H*), 7.92 (4 H, d, *J*=8.3 Hz, Ar*H*), 7.68 (4 H, d, *J*=8.3 Hz, Ar*H*) ppm; m/z (ESI) 417 (M+Na, 100%).

(*E*)-1,4-bis(4-methoxyphenyl)but-2-ene-1,4-dione:



This compound is known and is fully characterised.[39] 4'-methoxyacetophenone (0.150g, 1.00 mmol), $CuBr_2$ (0.0450g, 0.200 mmol), I_2 (0.506g, 2.00 mmol) and DMF (1.00 mL) were placed in a 15 mL ACE pressure tube and heated to 80 ^{0}C overnight with stirring. The reaction was worked up by addition of saturated $Na_2S_2O_4$ solution and extracted with ethyl acetate (3x20 mL). The solution was dried over anhydrous Na_2SO_4, filtered and solvent removed to give a yellow solid. Product was isolated via column chromatography eluted with 0-40% ethyl acetate in hexane to give a yellow solid (0.050g, 0.169 mmol, 34%). ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.07 (4 H, d, *J*=8.9 Hz, Ar*H*), 8.01 (2 H, s, C*H*=C*H*), 7.00 (4 H, d, *J*=8.9 Hz, Ar*H*), 3.90 (6 H, s, OC*H*$_3$) ppm; ^{13}C NMR (126 MHz, $CDCl_3$) δ 188.14, 164.20, 134.62, 131.36, 130.13, 114.14, 55.59 ppm; m/z (ESI) 319 (M+Na, 100%).

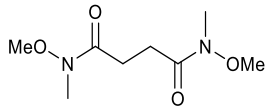
1,4-Bis(4-methoxyphenyl) -1,4-diol:



This compound is novel. 1,4-Bis(4-methoxyphenyl)butane-1,4-dione (296mg, 1.00 mmol) was placed in a dried and degassed (N_2 atmosphere) Schlenk tube and Ru(II)/TsDPEN catalyst (3.10mg, 5.00 µmol), formic acid/triethylamine (5:2, 1.00 mL) and anhydrous ethyl acetate (4.00 mL) were added. The reaction was heated with stirring to 40 ^{0}C for 64 hours. The reaction was worked up by addition saturated Na_2CO_3 and extraction with ethyl acetate (3x20 mL), dried over anhydrous $MgSO_4$, filtered and the reaction solvent was removed to give a brown residue. Product was isolated via column chromatography eluted with 0-70% ethyl acetate in hexane to give an off-white solid (280 mg, 0.927 mmol, 93%). Found 297.1121, $C_{19}H_{16}NNaO$ requires 297.1124; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.25 (4 H, d,

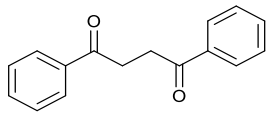
J=8.5 Hz, Ar*H*), 6.86 (4 H, d, *J*=8.5 Hz, Ar*H*), 4.50 - 4.80 (2 H, m, C*H*OH), 3.80 (6 H, s, OC*H*$_3$), 2.42 (2 H, br. s., O*H*), 1.84 - 2.00 (2 H, m, CHC*H*$_2$), 1.67 - 1.81 (2 H, m, CHC*H*$_2$) ppm; ^{13}C NMR (126 MHz, $CDCl_3$) δ 159.01, 136.79, 127.05, 113.81, 74.26, 55.27, 35.81 ppm; m/z 325 (100%, M+H).

N,N-dimethoxy-*N,N*-dimethylsuccinamide:



This compound is known and has been fully characterised.[55] MeOMeNH.HCl (18.9g, 194 mmol) was placed in a 250 mL round-bottom flask and DCM (100 mL) was added with stirring at room temperature. H_2O (10 mL) was added and a white precipitate dissolved after stirring for 30 minutes. K_2CO_3 (41.1g, 29.7 mmol) was added and effervescence was observed. After 30 minutes, succinyl chloride (10.0g, 64.6 mmol) in DCM (50 mL) was added at -78 ^{0}C. After stirring overnight, the reaction was quenched with saturated $NaHCO_3$ (90 mL) and extracted with DCM (3x60 mL). Solvent was removed on a rotary evaporator to give a brown oil and recrystallisation from toluene gave a near-white solid (8.24g, 40.4 mmol, 62%). ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.45 (6 H, br. s., NC*H*$_3$), 2.89 (6 H, br. s., OC*H*$_3$), 2.48 (4 H, br. s., C*H*$_2$C*H*$_2$) ppm; m/z (ESI) 205 (M+H, 100%).

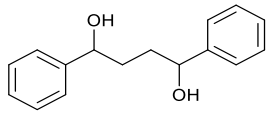
1,4-Diphenylbutane-1,4-dione:



This compound is known and has been fully characterised.[56] *N,N-N,N*-dimethoxy-*N,N*-dimethylsuccinamide (1.70g, 8.33 mmol) was placed in anhydrous THF (44 mL) with stirring at room temperature in a 100 mL round-bottom flask. After all solid had dissolved, the flask was cooled to 0 ^{0}C and PhMgBr in Et_2O (6.53 mL, 33.3 mmol) was added. The reaction was stirred at room temperature for 40 hours. The

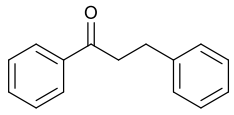
reaction was quenched with saturated NH_4Cl solution and THF was removed via a rotary evaporator. The product was extracted with DCM (3x30 mL). After removal of solvent, the product was washed with petroleum ether (3x30 mL) and the solid was collected via Buchner filtration to give a near-white solid (1.26g, 5.29 mmol, 64%). ^{1}H NMR (400 MHz, CDCl3) δ 8.05 (4 H, d, *J*=7.3 Hz, Ar*H*), 7.58 (2 H, t, *J*=7.3 Hz, Ar*H*), 7.49 (4 H, t, *J*=7.8 Hz, Ar*H*), 3.47 (4 H, s, CH_2CH_2) ppm; m/z (ESI) 261 (M+Na, 100%).

1,4-Diphenylbutane-1,4-diol:



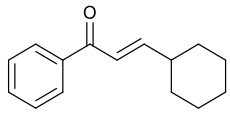
This compound is known and has been fully characterised.[57] 1,4-Diphenylbutane-1,4-dione (300mg, 1.27 mmol) was placed in a dried and degassed (N_2 atmosphere) Schlenk tube and Ru(II)/TsDPEN catalyst (3.10mg, 5.00 µmol), formic acid/triethylamine (5:2, 1.00 mL) and anhydrous ethyl acetate (4.00 mL) were added. The reaction was heated with stirring to 40 ^{0}C for 64 hours. The reaction was worked up by addition saturated Na_2CO_3 and extraction with ethyl acetate (3x20 mL), dried over anhydrous $MgSO_4$, filtered and the reaction solvent was removed to give a brown residue. Product was isolated via column chromatography eluted with 0-70% ethyl acetate in hexane to give an off-white solid (298mg, 1.23 mmol, 97%). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.06 - 7.54 (10 H, m, Ar*H*), 4.60 (2 H, d, C*H*OH), 3.51 (2 H, br. s., O*H*), 1.55 - 1.93 (4 H, m, CH_2CH_2) ppm; m/z (ESI) 259 (M+Na, 100%).

1,3-Diphenylpropan-1-one:



This compound is known and fully characterised.[58] (*E*)-1,3-diphenylprop-2-en-1-ol (210mg, 1.00 mmol) was placed in xylenes (0.5 mL) in a 15 mL ACE pressure tube with stirring. Tricarbonyl(1,8-bis(trimethylsilyl)octa-1,7-diyne)iron (41.8 mg, 0.100 mmol) and trimethylamine *N*-oxide (15.0 mg, 0.200 mmol) were added and the reaction solution was degassed via nitrogen bubbler for 15 minutes. The pressure tube was sealed and heated to 140 ^{0}C for 40 hours. The reaction was worked up by filtering the reaction material through celite with ethyl acetate and the solvent was removed by rotary evaporator to give a brown residue. Product was isolated via column chromatography eluted with 0-20% ethyl acetate in pentane to give a colourless oil (189 mg, 0.900 mmol, 90%). ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.96 (2 H, d, *J*=7.6 Hz, Ar*H*) 7.55 (1 H, m, Ar*H*) 7.45 (2 H, t, *J*=7.4 Hz, Ar*H*) 7.13 - 7.36 (5 H, m, Ar*H*), 3.31 (2 H, t, *J*=7.5 Hz, $COCH_2CH_2$), 3.07 (2 H, t, *J*=7.5 Hz, $COCH_2CH_2$) ppm; m/z (ESI) 233 (M+Na, 100%).

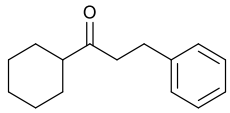
(*E*)-3-cyclohexyl-1-phenylprop-2-en-1-one:



This compound is known.[59] (*E*)-3-cyclohexyl-1-phenylprop-2-en-1-one (216mg, 1.00 mmol) was placed in xylenes (0.5 mL) in a 15 mL ACE pressure tube with stirring. Tricarbonyl(1,8-bis(trimethylsilyl)octa-1,7-diyne)iron (41.8 mg, 0.100 mmol) and trimethylamine *N*-oxide (15.0 mg, 0.200 mmol) were added and the reaction solution was degassed via nitrogen bubbler for 15 minutes. The pressure tube was sealed and heated to 140 ^{0}C for 40 hours. The reaction was worked up by filtering the reaction material through celite with ethyl acetate and the solvent was removed by rotary evaporator to give a brown residue. Product was isolated via column chromatography eluted with 0-20% ethyl acetate in pentane to give a

colourless oil (165 mg, 0.771 mmol, 77%). Found (ESI) 237.1248, $C_{15}H_{18}$ NaO requires 237.1250; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.61 - 7.59 (2 H, m, Ar*H* + COC*H*=CH), 7.34 - 7.41 (4 H, m, Ar*H*), 6.81 (1 H, d, *J*=16.0 Hz, COCH=C*H*), 2.66 (1 H, tt, *J*=11.1, 3.3 Hz, CH_2CHCH_2), 1.90 (2 H, d, *J*=13.6 Hz, CH*H*CHCH*H*), 1.84 (2 H, dt, *J*=12.20, 3.30 Hz, C*H*HCHC*H*H), 1.71 (1 H, d, *J*=12.1 Hz, C*H*H), 1.67 (1 H, s, CH*H*), 1.16 - 1.53 (4 H, m, CH_2) ppm; ^{13}C NMR (101 MHz, $CDCl_3$) δ 203.16, 142.22, 134.77, 130.30, 128.90, 128.27, 124.74, 49.43, 28.74, 25.93, 25.79 ppm; m/z (ESI) 237 (M+Na, 100%).

1-Cyclohexyl-3-phenylpropan-1-one:



This compound is known and has been fully characterised.[60] (*E*)-1-cyclohexyl-3-phenylprop-2-en-1-ol (216mg, 1.00 mmol) was placed in xylenes (0.5 mL) in a 15 mL ACE pressure tube with stirring. Tricarbonyl(1,8-bis(trimethylsilyl)octa-1,7-diyne)iron (41.8 mg, 0.100 mmol) and trimethylamine *N*-oxide (15.0 mg, 0.200 mmol) were added and the reaction solution was degassed via nitrogen bubbler for 15 minutes. The pressure tube was sealed and heated to 140 ^{0}C for 40 hours. The reaction was worked up by filtering the reaction material through celite with ethyl acetate and the solvent was removed by rotary evaporator to give a brown residue. Product was isolated via column chromatography eluted with 0-20% ethyl acetate in pentane to give a colourless oil (187 mg, 0.866 mmol, 87%). ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.03 - 7.14 (2 H, m. Ar*H*), 6.89 - 7.03 (3 H, m, Ar*H*), 2.69 (2 H, t, *J*=6.8 Hz, $COCH_2CH_2$), 2.56 (2 H, t, *J*=6.8 Hz, $COCH_2CH_2$), 2.01 - 2.24 (1 H, m, CH_2CHCH_2), 1.37 - 1.78 (25 H, m, CH_2), 0.83 - 1.26 (5 H, m, CH_2) ppm; m/z (ESI) 269 (M+Na, 100%).

(3.8) Abbreviations

^{0}C: degrees Celsius

mL: millilitre

µL: microlitre

psi: pounds per square inch

h: hour

FA/TEA: Formic Acid/Triethylamine (5:2)

CPME: Cyclopentyl Methyl Ether

Ar: Substituted phenyl ring

DMAP

g: gram

mg: milligram

mmol: millimole

µmol: micromole

ppm: parts per million

s: singlet

d: doublet

t: triplet

q: quartet

quin: quintet

ddt: doublet doublet of triplets

td: triplet of doublets

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